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Reliability analysis and modeling of the U. S. Marine Corps medium tactical wheeled vehicle in Operation Iraqi Freedom

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THESIS

RELIABILITY ANALYSIS AND MODELING OF THE U. S. MARINE CORPS MEDIUM TACTICAL WHEELED VEHICLE IN OPERATION IRAQI FREEDOM

by

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September 2007

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This thesis describes an analysis of the reliability of the Medium Tactical Vehicle Replacement (MTVR) cargo variant in Operation Iraqi Freedom (OIF), from March 1, 2004 to March 31, 2007. More than 870 MTVRs were fielded by the Marine Corps for OIF, of which 456 provided data for analysis. Analysis and modeling of this repairable system's failure modes are conducted at the MTVR variant, major unit, armored status, and subsystem levels to develop an understanding of the vehicle's usage and performance under field conditions. Reliability is measured by the frequency of occurrence of unscheduled maintenance events, with the number of days that a vehicle is not available due to these events ("deadlined days") used as a measure of severity. The challenges of using field maintenance and supply data are handled using various methods, including data verification, failure event aggregation, and odometer reading imputation. Nonparametric and parametric statistical methods are utilized, with system and subsystem failure mode recurrence data, to measure reliability throughout the period of observation and amidst the installation of system modifying vehicle armor kits. Reliability metrics are quantified to capture the effects of usage and armoring, taking into account that the MTVR is a repairable system.

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ABSTRACT

This thesis describes an analysis of the reliability of the Medium Tactical Vehicle Replacement (MTVR) cargo variant in Operation Iraqi Freedom (OIF), from March 1, 2004 to March 31, 2007. More than 870 MTVRs were fielded by the Marine Corps for OIF, of which 456 provided data for analysis. Analysis and modeling of this repairable system's failure modes are conducted at the MTVR variant, major unit, armored status, and subsystem levels to develop an understanding of the vehicle's usage and performance under field conditions. Reliability is measured by the frequency of occurrence of unscheduled maintenance events, with the number of days that a vehicle is not available due to these events ("deadlined days") used as a measure of severity. The challenges of using field maintenance and supply data are handled using various methods, including data verification, failure event aggregation, and odometer reading imputation. Nonparametric and parametric statistical methods are utilized, with system and subsystem failure mode recurrence data, to measure reliability throughout the period of observation and amidst the installation of system modifying vehicle armor kits. Reliability metrics are quantified to capture the effects of usage and armoring, taking into account that the MTVR is a repairable system.

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

AAV	Amphibious Assault Vehicle
CASC	Capability Assessment Support Center
CDD	Capabilities Development Document
CMC	Commandant of the Marine Corps
CNO	Chief of Naval Operations
COMUSMARCENT	Commander, U. S. Marine Forces Central Command
DIV	Marine Infantry Division
DRIS	Date Received In Shop
EDL	Equipment Density List
ERO	Equipment Repair Order
GLM	Generalized Linear Model
HMMWV	High Mobility Multi-Wheeled Vehicle
HPP	Homogeneous Poisson Process
IED	Improvised Explosive Device
IETM	Integrated Electronic Technical Manual
LAV	Light Armored Vehicle
LVS	Logistics Vehicle System
LVSR	Logistics Vehicle System Replacement
MARCORLOGCOM	Marine Corps Logistics Command
MARCORSYSCOM	Marine Corps Systems Command
MARES	Marine Corps Automated Readiness Evaluation System
MAS	MTVR Armor System
MAW	Marine Aircraft Wing
MCBul	Marine Corps Bulletin
MCF	Mean Cumulative Function
MDR	Master Data Repository
MHG	Marine Expeditionary Force Headquarters Group
MIMMS AIS	Marine Corps Integrated Maintenance Management System Automated Information System
MLE	Maximum Likelihood Estimate
MLG	Marine Logistics Group
MOE	Measure Of Effectiveness
MP	Military Police
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
MTVR	Medium Tactical Vehicle Replacement
NHPP	Nonhomogeneous Poisson Process
NSN	National Stock Number

OIF	Operation Iraqi Freedom
ORD	Operational Requirements Document
RDD	Required Delivery Date
ROCOF	Rate of Occurrence of Failure
SASSY	Supported Activities Supply System
SOE	System Operational Effectiveness
SORTS	Status of Resources and Training System
SPLIDA	S-PLUS Life Data Analysis
TAMCN	Table of Authorized Materiel Control Number
TLCM-AT	Total Life Cycle Management Assessment Tool
TO&E	Table of Organization and Equipment
UIC	Unit Identification Code
USMC	United States Marine Corps
VV&A	Verification, Validation, and Accreditation
WIR	Recoverable Items Report
WOLPH	Recoverable Items Report Online Process Handler

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This thesis is dedicated to Corporal Chad W. Powell, United States Marine Corps, who, while performing his duties as a Marine and Medium Tactical Vehicle Replacement operator with Regimental Combat Team Eight, was killed during combat operations in Fallujah, Iraq on June 23, 2005.

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EXECUTIVE SUMMARY

The United States Marine Corps' involvement in Operation Iraqi Freedom (OIF) places increased demand on all types of ground equipment. Operations in Iraq have Marine Corps units widely dispersed in Al Anbar province, a battle space the size of Utah, creating the requirement for an extended logistics support structure. The backbone of this structure at the tactical level is the medium tactical wheeled vehicle, formally known as the Medium Tactical Vehicle Replacement (MTVR). The 874 cargo variant MTVRs in Iraq enable the distribution of materiel that supports combat operations, force protection measures, and daily life support requirements. These operating conditions demand more from the MTVR than a garrison environment does, thereby accelerating the vehicle's aging process and modifying its nominal life cycle.

The Marine Corps' current need for reliability analysis and modeling stems from the duration of OIF and the costs of procuring and sustaining military ground equipment. These two factors impact how equipment is managed in support of operational plans and how funding is allocated for equipment life cycle requirements. The 34th Commandant of the Marine Corps addressed these factors in his 2006 Commandant's Planning Guidance by identifying the requirement to "Develop better readiness and sustainment indicators based on predictive modeling, so that timely changes to strategies, plans, and programs can be implemented" (CMC, 2006, p. 10). This statement identifies a capability shortfall in the area of equipment reliability modeling, and highlights that capability's importance in strategic and operational level logistics.

The degree to which OIF has accelerated vehicle age and impacted vehicle reliability is difficult to quantify. The existing Marine Corps maintenance and supply information systems do not directly answer these questions, nor do unit readiness reports or program level databases. Therefore, a detailed analysis is necessary to determine system performance in the area of reliability, and to create a predictive model of system and subsystem reliability based upon predominant operational factors. This information can be used to improve the planning, estimation, and decisions that are made for MTVR employment, sustainment, and disposal.

Reliability is the probability that a system or component will perform its intended function under operating conditions, for a specified period of time (Meeker and Escobar, 1998, p. 2). As system reliability increases, the frequency of unscheduled maintenance decreases; conversely, as system reliability decreases, the frequency of unscheduled maintenance increases.

The primary objectives of this thesis are to conduct a reliability analysis of the MTVR in OIF and to create a predictive model of MTVR system and subsystem reliability. A secondary objective is to provide a methodology for reliability analysis and modeling of Marine Corps ground equipment that can be referenced and utilized by maintenance managers, materiel managers, operations analysts, and program managers.

This thesis' analysis focuses on three areas to develop an understanding of the MTVR's reliability in OIF. These areas are operational use and performance, non-parametric statistical methods for reliability analysis and modeling, and parametric statistical methods for reliability analysis and modeling.

Operational use and performance addresses the MTVR's utilization and performance at the tactical level. Utilization is identified by the system's usage rate, which is a factor of miles driven over operational time. Usage rate is a key element in reliability analysis and modeling because it provides a valid measure of the system operating age. Performance is measured by the amount and type of maintenance activity that the system requires, which is documented by failures at the subsystem level. The type and frequency of failures within variants, by unit, and by armor status provides an understanding of system and subsystem failure trends in the operating environment.

A non-parametric statistical method for reliability analysis of repairable system recurrence data is based upon a cumulative plot of system or subsystem failure times. This method utilizes the Mean Cumulative Function (MCF) to visually represent average system or subsystem performance (Nathan and Trindade, 2006). The MCF is applied at the system and subsystem levels to identify trends and make comparisons between variants, units, and armor status.

Recurrence data is also used in parametric statistical methods for reliability analysis and modeling. Failure event recurrence data are modeled as a Power Rule Non-Homogeneous Poisson Process. Recurrence data, that are found to match a homogeneous Poisson process model, are used to determine common reliability measures of effectiveness, including failure rate and Mean Time Between Failure (MTBF). Further modeling is conducted at the system level, using Poisson regression, to determine failure rate and MTBF based upon variant, unit, and armor status.

I. INTRODUCTION

A. BACKGROUND

The United States Marine Corps’ involvement in Operation Iraqi Freedom (OIF) places increased demand on all types of ground equipment. Operations in Iraq have Marine Corps units widely dispersed in Al Anbar province, a battle space the size of Utah, creating the requirement for an extended logistics support structure. The backbone of this structure at the tactical level is the medium tactical wheeled vehicle, formally known as the Medium Tactical Vehicle Replacement (MTVR). The 874 cargo variant MTVRs in Iraq enable the distribution of materiel that support combat operations, force protection measures, and daily life support requirements. These operating conditions demand more from the MTVR than a garrison environment does, thereby accelerating the vehicle’s aging process and modifying its nominal life cycle.

The Marine Corps' operating environment in Al Anbar province, Iraq's western region, consists of an arid climate amidst dispersed small urban areas and open desert. Temperatures range from 110 degrees Fahrenheit in the summer months to 37 degrees Fahrenheit in the winter months. Precipitation occurs during the winter months at an average of 1 inch per month, while the summer months receive no precipitation. The road network and conditions range from modern highways near Baghdad to unimproved roads in the Syrian Desert. Combat operations require the MTVR to use the existing road network, unimproved roads, and accessible desert terrain. MTVR staging areas are predominantly uncovered sand lots, while maintenance areas are open-air covered hard-surface facilities. Desert sand and silt permeate all areas with the aid of desert winds and seasonal sand storms, which have the ability to reduce visibility to levels where vehicle movement is unsafe. Movement throughout the battle space is further complicated by the existence of insurgent forces. These forces leverage the vulnerable road network to their advantage by emplacing ambushes. These ambushes utilize small arms fire, Improvised Explosives Devices (IEDs), and mines to disrupt and destroy Marine forces. Convoy procedures incorporate measures to minimize the risk from these ambushes and the MTVR has received several armor upgrades to protect its crew, passengers, and cargo in case of attack.

Reliability is commonly defined as the probability that a system or component will perform its intended function under operating conditions, for a specified period of time (Meeker and Escobar, 1998, p. 2). The Marine Corps' current need for reliability analysis and modeling stems from the duration of OIF and the costs of procuring and sustaining military ground equipment. These two factors impact how equipment is managed in support of operational plans and how funding is allocated for equipment life cycle requirements. The 34th Commandant of the Marine Corps addressed these factors in his 2006 Commandant's Planning Guidance by identifying the requirement to "Develop better readiness and sustainment indicators based on predictive modeling, so that timely changes to strategies, plans, and programs can be implemented" (CMC, 2006, p. 10). This statement identifies a capability shortfall in the area of equipment reliability modeling, and highlights that capability’s importance in strategic and operational level logistics.

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B. MEDIUM TACTICAL VEHICLE REPLACEMENT

The MTVR is produced by Oshkosh Truck Corporation and has been in service in the Marine Corps since initial fielding between 2001 and 2003. This medium truck is the "workhorse" of the Marine Corps and fills the gap between the light vehicle fleet of High Mobility Multipurpose Wheeled Vehicles (HMMWVs) and the heavy vehicle fleet of Logistics Vehicle Systems (LVSs). While the MTVR family of vehicles includes dump and wrecker variants, the focus of this thesis is the cargo variant, which includes the standard bed and extended bed models shown in Table 1. The MTVR cargo variant is the primary vehicle that delivers supplies to forward-deployed units and that also reinforces the line-haul capability of the LVS. The capabilities of the

MTVR include towing weapon systems and transporting personnel, ammunition, break-bulk cargo, bulk liquids, cargo containers, and engineer equipment.

ID Number	**Variant Description**
10629A	Standard Bed
10629B	Standard Bed, with Winch
10629C	Standard Bed, Armored
10629D	Standard Bed, with Winch, Armored
10631A	Extended Bed
10631B	Extended Bed, with Winch
10631D	Extended Bed, Armored
10631E	Extended Bed, with Winch, Armored

Table 1. MTVR Cargo Variants.

The MTVR mission profile specifies 70 percent cross-country use and 30 percent highway use, with a 7.1 ton and 15 ton payload, respectively. The cargo variant specifications are in Appendix A and the baseline unarmored model, variant ID number 10629A, is shown in Figure 1. (Oshkosh Truck Corporation, 2005)

Figure 1. MTVR Cargo Variant, ID Number 10629A (GlobalSecurity.org, 2006).

The Capability Development Document establishes reliability measures Of effectiveness (MOEs) to guide the development of a system that will meet operational mission performance standards. A comprehensive list of the MTVR's reliability MOEs is provided in Appendix A, with the applicable MOEs to this thesis shown below (USMC, 1997, p. 10):

- Mean Miles Between Operational Failures: 2000 miles (minimum), 4000 miles (objective)
- Probability of completing a 200 mile mission without a mission failure: 0.90 (minimum), 0.95 (objective)

- Achieved availability: 0.89 (minimum), 0.90 (objective)
- Service Life: 0.70 probability of completing 77000 miles (minimum) during its estimated 22 year service life without replacement of a major component, e.g., engine, transmission, drive train, cooling system, electrical system, etc. (objective).

The MTVR is a repairable system that can be returned to operating status after a failure has occurred by replacing parts or adjusting settings. Repairable systems that fail have recurring maintenance and supply requirements that may change over time. Mechanical systems often degrade and are not returned to as-new condition upon repair; consequently, times between repair events typically decrease in a degrading system. These failure and repair events occur within the MTVR's subsystems, which combine to provide the vehicle's capabilities and reliability. Examples of MTVR subsystems include the axle/suspension system (AXLE/SUSP), body (BODY), electrical system (ELEC), and engine (ENG). The complete MTVR subsystem list, with accompanying components, is provided in Appendix A.

The focus of this thesis is to measure system and subsystem performance by analyzing unscheduled maintenance events at the subsystem level. Unscheduled maintenance events, generally referred to as a failure, are categorized as deadlining or non-deadlining according to the following criteria:

- Deadlining failure: A failure that requires critical repairs and makes the system not mission capable.

- Non-deadlining failure: A failure that degrades system capabilities or requires non-critical maintenance.

From the beginning of OIF in 2003, the Marine Corps has focused on providing armor protection for all of its motor transport equipment. The goal has been to provide the best protection possible to each of its vehicles in Iraq (Catto, 2006, p. 7). To that end, the Marine Corps and Oshkosh Truck Corporation developed the MTVR Armor System (MAS), consisting of metal composite panel armor and Mil-A-46100 high hard steel armor for the cab and troop carrier (Marine Corps Systems Command, 2007). The MAS, which was installed on all Iraq MTVRs between May 2005 and March 2006, is capable of withstanding small arms fire, IEDs, and mine blasts from up to 12 lbs of High Explosives. The armor solutions prior to the MAS were far less substantial, providing less protection to the crew, passengers, cargo, and vehicle. The two types of MAS armor outfit the vehicle undercarriage and cab, or the vehicle undercarriage, cab, and troop carrier. The significant aspects of the MAS, in relation to this thesis, are that it is a permanent modification to the MTVR that adds approximately 4000 lbs (cab armor kit) to 10,500 lbs (cab and troop carrier armor kits) to the vehicle's weight. The remaining MAS specifications are provided in Appendix A. A photograph of an MTVR with the installed MAS (cab and troop carrier armor kits) is shown in Figure 2.

Figure 2. MTVR with MAS Cab and Troop Carrier Armor Kit (Defense Update, 2004).

The MTVR cargo variant is selected as the equipment type for reliability analysis and modeling for the following reasons:

- The MTVR is a reportable system in the Status of Resources and Training System (SORTS). SORTS reportable systems collectively provide a measure of a unit's overall equipment status or capability (MCBul 3000, 2007).
- The MTVR is a comparatively new vehicle that has not undergone a rebuild program that could alter the system's reliability profile.
- The MTVR vehicle fleet has not participated in a systematic rotation plan during OIF. The vehicles have been in Iraq since Marine Corps units re-entered the country in February 2004, with the exception of vehicles that have replaced combat losses and vehicles distributed in support of the MAS armor installation process. This provides a continuous three-year period in which to observe

and collect system data with minimal changes in predominant operational and environmental factors.

- Of the Marine Corps' ground equipment in Iraq, the MTVR provides a balance between the quantity available for sampling and the system cost. Among tracked and wheeled vehicles, the MTVR ranks second only to the HMMWV (COMUSMARCENT G4, 2007; United States Marine Corps, 2007).
- MTVR usage data from recorded odometer readings are available from several sources. Because usage data are an important element in reliability analysis and modeling, this is a key consideration for selecting the MTVR for study.

C. SYSTEM AVAILABILITY AND RELIABILITY THEORY

System availability and readiness are synonymous terms that represent the degree, percentage, or probability that a system will be available when required for use. Reliability is an element of availability, along with maintainability and supportability. These performance measures are used during system design, development, and sustainment to optimize performance throughout a system’s life cycle (Blanchard, 2004, p. 72).

For the Marine Corps, high levels of equipment availability are necessary for tactical operations to be efficient and effective. Tactical level planners and logisticians use historical trends in equipment availability to estimate the quantity that will be available for current and future operations. At the operational and strategic levels of war, forecasts of equipment availability project further into the future and have a broader impact. Forecasts at these levels impact equipment rotation policies, acquisition decisions, budget planning, secondary repairable inventory levels, and other resource requirements.

In reliability measurement, systems use “time” as an appropriately chosen metric to reflect usage: miles driven, hours of operation, etc. Statisticians and reliability engineers distinguish between “repairable” and “non-repairable” systems when characterizing reliability. As its name suggests, a repairable system is subject to repeated failure-repair cycles during its lifetime. Reliability focuses on the times between failure events; or equivalently, on the number of failure events that occur during a given period of time. A typical pattern for a repairable system is an increasing rate of failures (decreasing time between failures) occurring as the system ages. This is because repairs are not fully successful in restoring the system to “as-new” condition as stress and wear take their toll.

Measures of reliability that are used with non-repairable systems, such as the mean time to failure (MTTF) determined when the system is new, can give a misleading characterization of reliability for a repairable system. Measures appropriate for repairable systems include the Mean Cumulative Function (MCF) and the Rate Of Occurrence Of Failures (ROCOF) (NIST, 2003). The MCF is a function of time, denoted $\mu(t) = E[N(t)]$, which gives the expected number of failures $N(t)$ that occur up to time t. The ROCOF also is a function of time, denoted $m(t) = \mu'(t)$, which is the first derivative of the MCF. The ROCOF gives a measure of the instantaneous rate of failure at a particular time.

A lifetime distribution model is represented by a probability density function $f(t)$ that ranges from time $t = 0$ to $t =$ infinity. The cumulative distribution $F(t)$ is the probability that a system will fail by time t, which is obtained by integrating the density function:

$$F(t) = P(T \le t) = \int_0^t f(u)du \ ,$$

where T is a random variable denoting lifetime. Common lifetime distribution models, that can be used when the ROCOF is constant, include the exponential, Weibull, gamma, and lognormal distributions.

D. INFORMATION SYSTEMS AND TOOLS

The Marine Corps Integrated Maintenance Management System Automated Information System (MIMMS AIS) provides essential maintenance management information for logistics planning and decision making. MIMMS AIS data entry is performed by the mechanic or MIMMS clerk, in the unit maintenance shop or maintenance management office, as maintenance is conducted on equipment. Maintenance requirements are translated into supply requirements that are requisitioned through the Supported Activities Supply System (SASSY). These requisitions are tracked in SASSY and receive status updates until they are received by the requesting unit. Historical data generated by MIMMS AIS and SASSY are archived within the Marine Corps' Master Data Repository (MDR). The MDR, managed by the Marine Corps Logistics Command (MARCORLOGCOM), is continuously updated and can be queried for data in support of logistics studies and analysis.

The System Operational Effectiveness (SOE) tool, managed by the Capability Assessment Support Center (CASC), Marine Corps System Command (MARCORSYSCOM), is an automated tool that enables logisticians, materiel managers, and program managers to monitor and improve system operational effectiveness throughout a system's life cycle. Relying upon field maintenance and supply data in the MDR, the SOE tool utilizes algorithms to measure system performance in the areas of availability, maintainability, reliability, and supportability (CASC, 2006). This thesis builds upon the analysis capabilities within the SOE tool by conducting analysis at the unit, MTVR variant, and subsystem levels, and by incorporating system usage rates into failure mode analysis and modeling.

The Total Life Cycle Management – Assessment Tool (TLCM-AT) is the Marine Corps' first endeavor to use stochastic modeling and simulation analysis to achieve higher ground equipment readiness. The tool is currently under development by Clockwork Solutions and will be available in 2008 for the following systems: Amphibious Assault Vehicle (AAV), Light Armored Vehicle (LAV), Light Weight 155mm Howitzer, Logistics Vehicle System Replacement (LVSR), and Medium Tactical Vehicle Replacement (MTVR). TLCM-AT is being designed to draw upon data within the MDR and SOE tool to perform Monte Carlo simulations of the life cycle behavior of aging systems in various operational environments. The tool utilizes a data model built upon the system's subsystem configuration, whereby subsystem failure times are independent and exponentially distributed. Operational and logistics considerations are incorporated in order to provide forecasts of operating and support costs, maintenance and supply performance, and system readiness (Clockwork Solutions, 2006). This thesis augments the TLCM-AT MTVR model and output by conducting analysis at the unit, MTVR variant, and subsystem levels, and by incorporating system usage rates into failure mode analysis and modeling.

E. SCOPE OF THESIS

The primary objectives of this thesis are to conduct a reliability analysis of the MTVR in OIF and to create a predictive model of MTVR system and subsystem reliability. A secondary objective is to provide a methodology for reliability analysis and modeling of Marine Corps ground equipment that can be referenced and utilized by maintenance managers, materiel managers, operations analysts, and program managers. The following questions are addressed to support these objectives:

- What data are needed and where is it stored?
- What is the quality of the data?
- What measures must be taken to prepare the necessary data for reliability analysis and modeling?
- What are the MTVR usage levels in OIF?
- What is the OIF reliability performance of the MTVR and its subsystems?
- What parametric and non-parametric statistical methods can be used for reliability analysis and modeling of the MTVR? What are the results of using these methods?

The analysis presented in this thesis focuses on three areas to develop an understanding of the MTVR's reliability in OIF. These areas are operational use and performance, non-parametric statistical methods for reliability analysis and modeling, and parametric statistical methods for reliability analysis and modeling.

Operational use and performance addresses the MTVR's utilization and performance at the tactical level. Utilization is identified by the system's usage rate, which is the number of miles driven over vehicle operational time. Usage rate is a key element in reliability analysis and modeling because it provides a valid measure of the system operating age. Performance is measured by the amount and type of maintenance activity that the system requires, which is documented by failures at the subsystem level (axles and suspension, engine, electrical, etc.). Tracking the types and frequencies of failures within variants, before and after MAS armor installation, and by unit helps in developing an understanding of system and subsystem failure trends in the operating environment.

A non-parametric statistical method for reliability analysis of repairable system recurrence data is based on the Mean Cumulative Function (MCF) (Meeker and Escobar, 1998). The MCF can be plotted against time to visually represent average system or subsystem performance (Nathan and Trindade, 2006). The MCF is applied at the system and subsystem levels to identify trends and to make comparisons between variants, by vehicle usage rate, by major unit, and before and after MAS armor installation.

Recurrence data will also be analyzed using a parametric statistical method for reliability analysis and modeling. In this method, failure events will be modeled as a Poisson process with either a constant or nonconstant recurrence rate. Analysis at the system and subsystem levels will enable Poisson process parameter estimation, confidence interval estimation, and checks for adequacy of the appropriate predictive model.

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II. DATA AND METHODOLOGY

A. MTVR SAMPLE

This thesis focuses on a sample of 456 cargo variant MTVRs taken from a population of 874 cargo variant MTVRs operating in OIF between March 1, 2004 and March 31, 2007. The selection of vehicles for the sample is constrained by the availability of armoring information from MARCORSYSCOM. Under this constraint, the goal is to create a sample of approximately 50 percent of the population, with equal representation of each cargo variant and major OIF unit. The final sample used for analysis consists of 398 vehicles taken from MARCORSYSCOM's MAS armor installation database, and the remaining 58 vehicles selected from the OIF population to achieve the equal representation of cargo variants and units. These units are the Marine Expeditionary Force (Forward) Headquarters Group (MHG), Marine Division (DIV), Marine Aircraft Wing (MAW), Marine Logistics Group (MLG), and Military Police (MP). Breakdowns of the sample by MTVR variant and unit are shown in Table 2 and Table 3, respectively.

ID Number	**Variant Description**	**Quantity**
10629A(10629C)	Standard Bed (MAS)	306
10629B(10629D)	Standard Bed with Winch (MAS)	67
10631A(10631D)	Extended Bed (MAS)	56
10631B(10631E)	Extended Bed with Winch (MAS)	27

Table 2. Sample Composition by MTVR Variant.

Unit	Quantity
MHG	68
DIV	166
MAW	65
MLG	129
MP	28

Table 3. Sample Composition by Unit.

The nominal period of observation for MTVRs in the study is the 37-month period starting on March 1, 2004 and ending on March 31, 2007. Although most vehicles were available for the entire 37-month period of observation, the periods of observation for some vehicles were shorter due to fielding after March 1, 2004, sourcing from OIF excess stocks during the period of observation, or combat loss. Table 4 shows the distribution of MTVR observation lengths, and Table 5 shows the vehicle age summary statistics at the start of the period of observation.

Months Observed	Vehicle Quantity
0 – 5	1
6 – 10	0
11 - 15	4
16 - 20	66
21 - 25	3
26 - 30	5
31 - 36	15
37	362

Table 4. Period of Observation for Vehicles in the Study.

		Min	1st Quartile	Median	Mean	3rd Quartile	Max
Standard Bed	Days Since Fielding	0	457	548	576	640	1333
	Miles Driven	10	107	2625	5367	7948	44131
Extended Bed	Days Since Fielding	107	442	572	569	704	990
	Miles Driven	14	112	1697	3776	4737	37738

Table 5. Summary Statistics of Vehicle Age at the Start of the Period of Observation.

MAS armor installation was completed during each vehicle's period of observation. Because the armoring of the MTVR fleet in OIF occurred over 11 months, the armoring date for each vehicle varies depending on when the vehicle was processed through the in-theater MAS installation facilities. The mean miles accumulated by the sample MTVRs upon receiving the MAS armor is 12,398 ± 1,011 (95 percent confidence interval). Additionally, Figure 3 provides a breakdown of the before MAS armor and after MAS armor installation time periods for the vehicles in the sample. A balance between these time periods is desired in order to facilitate analysis of the impact of the MAS on the MTVR's reliability.

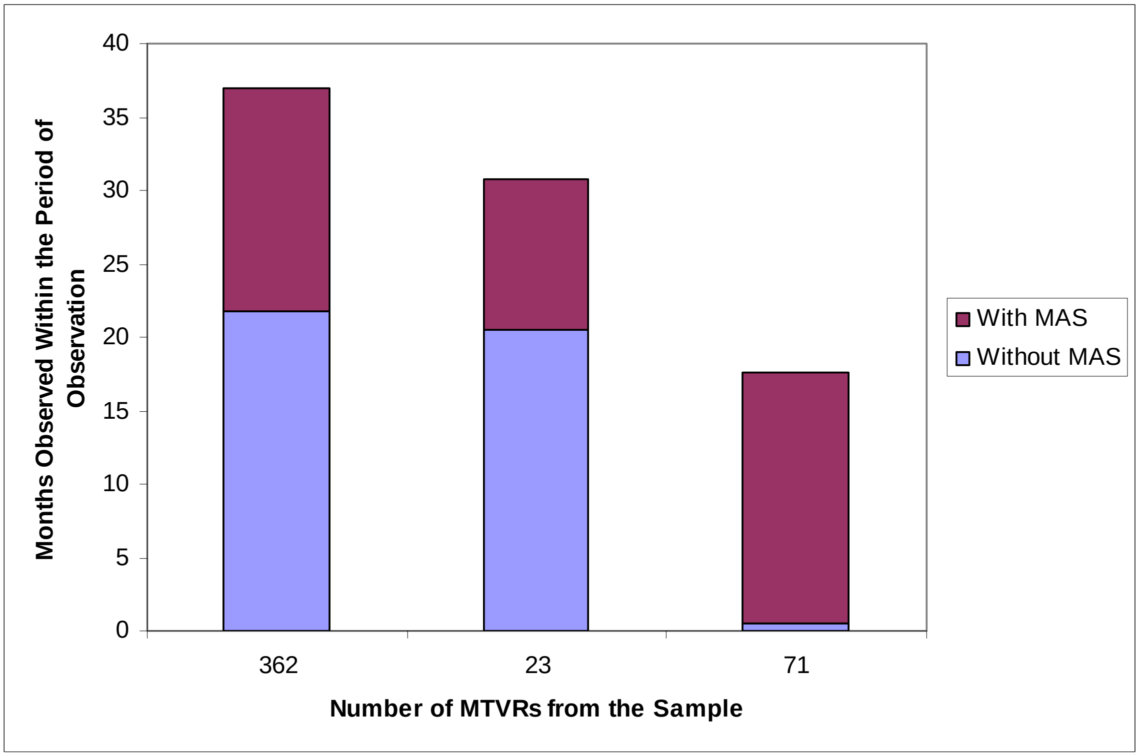

Figure 3. Summary of Vehicle MAS Armor Status Within the Period of Observation.

B. DATA SETS AND RESOURCES

The reliability analysis of the MTVR presented in this thesis would not have been possible without consolidating data from several sources. Each source either provided unique data or data that were used to reinforce or validate existing data.

The primary source of maintenance and supply data is the MDR at MARCORLOGCOM. Data queries are submitted to the Studies and Analysis Department, MARCORLOGCOM, for deployed Marine Corps units during the period of observation. Maintenance data are extracted from the Equipment Repair Order (ERO) history file in the MDR. The ERO is the document that captures maintenance actions and requirements as maintenance is performed on equipment. Appendix B presents an example of the MTVR ERO history data used in the thesis research. Maintenance actions that require repair parts rely on SASSY for repair part requisitioning and tracking. SASSY repair part requisitions, referenced by ERO numbers, are pulled from the repair parts history file in the MDR. Appendix C displays an example of the MTVR repair part history data extracted from SASSY.

The data sets received from sources often contain more information than is needed to perform reliability analysis and modeling. Therefore, reducing the data sets to only the essential data elements is necessary. A summary of the essential data elements from the ERO history and Repair Parts history files is provided in Appendix D.

Additional data are needed to obtain a comprehensive understanding of the events in a sample MTVR's lifecycle. They include manufacturing dates, fielding dates, MAS armoring information, and combat loss information. Manufacturing and fielding dates are obtained from Oshkosh Truck Corporation. The manufacturing date represents the date that a Marine Corps representative takes possession of a newly manufactured vehicle. The Required Delivery Date is the fielding date for a vehicle to its respective Marine Corps unit. The next key event in the life of a fielded MTVR is the MAS armoring process, for which information is provided by the Program Manager Motor Transportation, MARCORSYSCOM. This information contains the date that a vehicle completes the MAS armoring process, along with the type of MAS armor installed. Lastly, if a vehicle is destroyed during combat operations, the vehicle is considered a combat loss and its period of observation ends. Documentation of MTVR combat loss dates is obtained from the Recoverable Items Report (WIR) Online Process Handler (WOLPH) database at MARCORLOGCOM.

To facilitate analysis, other information is derived from the data received from the aforementioned resources. The five major units, which encompass all Marine Corps operating forces in OIF, are identified by the Unit Identification Code (UIC) in MIMMS. The type of maintenance conducted on a vehicle is categorized as scheduled or unscheduled. These maintenance categories are recognized by using the Defect Code in MIMMS. A list of Defect Codes produced by the sample MTVRs during the period of observation is provided in Appendix E. For the purpose of analysis, vehicle failures in the field are assumed to be represented as unscheduled maintenance events. Unscheduled maintenance beyond a unit's local (organic) capability is handled by a higher level of maintenance capability. This situation must be identified to accurately represent the time a vehicle is in the maintenance process. A maintenance event is categorized by the subsystem for which maintenance action is required. Subsystem groups generated from Defect Codes are identified in Appendix E, while subsystem groups generated from repair part requisitions are identified using the subsystem configuration and parts list in the MTVR Integrated Electronic Technical Manual (IETM) (Oshkosh Truck Corporation, 2004).

C. DATA QUALITY

The quality of data used in reliability analysis and modeling directly affects the accuracy of the results. With this in mind, a specific effort is made to review and improve the quality of the data.

The ERO history data requires considerable review and improvement before use. The elements of the ERO history data that require improvement are the ID Number, Table of Authorized Materiel Control Number (TAMCN), Defect Code, and odometer reading. Following the review and correction of ID Numbers and TAMCNs, a comparison is made with the original data. The results of the comparison are in Table 6.

	Correct ID Number	**Correct TAMCN**
No MAS	86.42%	95.57%
MAS	71.21%	72.73%
Overall	78.04%	82.98%

Table 6. Accuracy of Vehicle Information in ERO History Data.

The TAMCN has a higher accuracy because it is a broader designation than the ID Number. MTVRs with MAS have the lowest accuracy even though MAS installation is a permanent modification to the MTVR, changing the ID Number and TAMCN. These designation changes are a reason for the low accuracy.

Defect Code accuracy is also measured through a comparison with repair part requisitions, of which 53.5 percent of EROs have. Of the EROs with repair part requisitions, only 23.5 percent have a Defect Code subsystem failure mode that matches the subsystem failure mode generated from repair part requisitions. Failure identification of a specific subsystem through repair part requisitions is considered reliable because it is generated from SASSY data, based upon the highest requisition priority and largest subsystem cost within the ERO. Defect Code accuracy is based upon the proficiency and attention to detail of the mechanic who is creating the ERO, and therefore is less objective and more subjective.

The usage age of a vehicle is represented by the number of miles it has accumulated. Marine Corps equipment has mileage documented each time an ERO is created. Unfortunately, the mileage records are not accurate enough to use without detailed review and refinement. Within the period of observation, and with the use of odometer readings from two other sources, 45.3 percent of MTVR ERO history odometer readings are determined to be useful for analysis. The low percentage of usable odometer readings is a result of human and system factors, including:

- Errors in the manual transfer of the odometer reading from the vehicle, to the ERO, and into MIMMS AIS.
- Entries that are not odometer readings, i.e., 12345, 343434, or 9999.
- The incorrect recording of the hour-meter on the tachometer dial as the odometer reading.
- The side by side placement in the instrument panel of the tachometer dial, containing the hour-meter, and the speedometer dial, containing the odometer. This placement is shown in Figure 4.
- The odometer is digital while the hour-meter is analog. The hour-meter reading is always visible while the odometer reading is only visible when vehicle electrical power is on. This factor is shown in Figure 5.

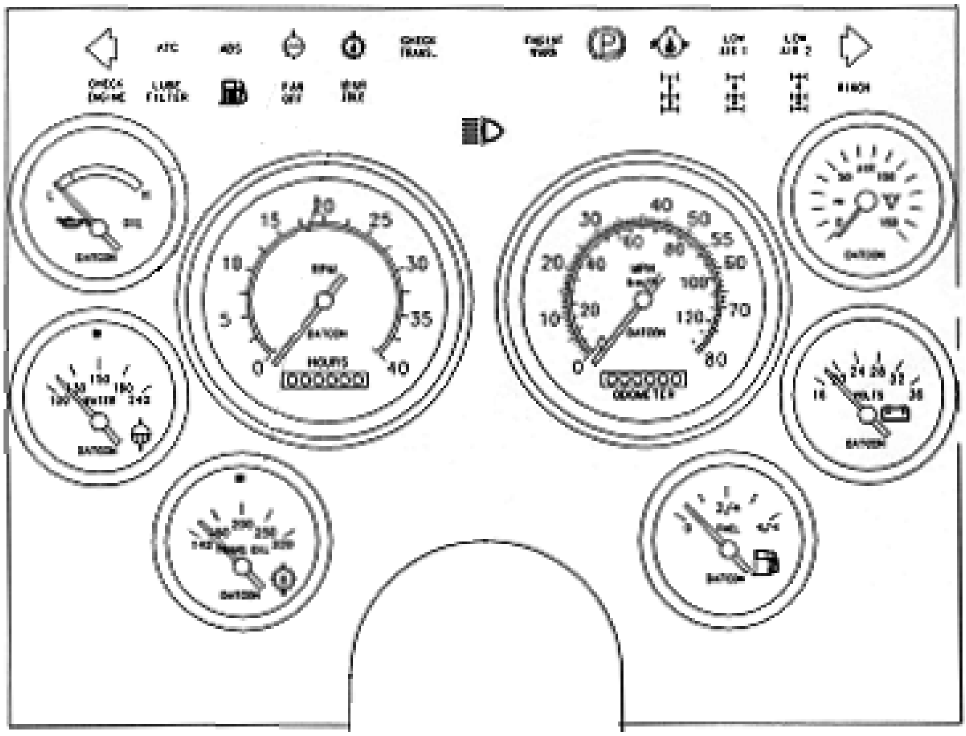

Figure 4. MTVR Instrument Panel (Oshkosh Truck Corporation, 2004).

Figure 5. MTVR Hour Meter and Odometer (Oshkosh Truck Corporation, 2004).

The quality of the repair part requisition data is degraded only by occasional requisitions for items that are not MTVR repair parts. These items include repair parts for small arms, maintenance shop supplies, office supplies, and uniform items. Each of these items is categorized to not affect reliability analysis and modeling. The manufacturing dates, fielding dates, MAS armoring information, and combat loss information have no noticeable data quality issues.

D. DATA REFINEMENT

Refinement of the MTVR sample data is necessary in order to recover as much information as possible from odometer readings, to manage data censoring and truncation, and to recognize repeat sequential failures due to poor maintenance or poor maintenance quality control. Data refinement significantly improves the quality and quantity of useful data in the sample.

Odometer readings obtained from a vehicle's maintenance history are regarded as valid through the use of the following rules:

- Odometer readings are non-decreasing over time;
- Upon identification of a legitimate odometer reading, if the subsequent readings beyond the next ERO are the same as the legitimate odometer reading, they are not legitimate;
- Patterns such as 9999, 232323, 12345, and 9876 are not legitimate;
- Increases greater than 2000 miles per month are not legitimate;
- An odometer reading that closely matches an odometer reading taken from another source is legitimate.

Where possible, odometer readings that are not usable are approximated by imputation using valid odometer readings. Imputation occurs through interpolation between two usable odometer readings and their respective dates, providing a usable odometer reading history for each vehicle with at least two originally usable odometer readings. Additionally, extrapolation with the unit daily mean usage rate is used to estimate odometer readings at the beginning and end of a vehicle's maintenance history, and for vehicles with only one usable odometer reading. The odometer reading imputation procedure is illustrated in Table 7.

Event	Date	Usable Meter Reading	Daily Usage Rate to Next Event	Days Deadlined	Operational Days to Next Event	Imputed Meter Reading
Start Obs.	3/1/2004		15		191	34447
Failure	9/8/2004		15		493	37384
Sched. Maint.	1/14/2006	44964	36	53	66	
Sched. Maint.	5/13/2006		36		10	47310
Failure	5/23/2006	47665	17	1	7	
Sched. Maint.	5/31/2006		17		19	47784
Sched. Maint.	6/19/2006	48107	51	8	111	
Failure	10/16/2006	53723	15	24	142	
End Obs.	3/31/2007					55906

Table 7. Example of Odometer Reading Imputation.

As is typical of reliability studies, some failure times are right censored at the end of the observation period for each vehicle. Similarly, failure events that occur before the beginning of the observation period are not observed, and are formally regarded as truncated (Meeker and Escobar, 1998, p. 41). Censoring and truncation must be recognized in reliability analysis and modeling, and are managed through data formatting and the statistical software used.

Repeat sequential failures of the same subsystem are found periodically in the ERO history data. When the same subsystem fails within a short period of time, it can be a result of poor maintenance quality. Post maintenance quality control checks exist to detect inadequate maintenance, but these checks do not completely eliminate the need to repeat maintenance actions on the same problem. Because repeat sequential failures of this nature will distort analyses and modeling, they are removed from the data. Specifically, a repeat sequential failure is removed from the data if it occurs within seven days of the previous failure within the same subsystem, and if there are no intervening failures from different subsystems.

E. DATA FORMATTING FOR ANALYSIS AND MODELING

The final step before conducting analysis and statistical modeling is to format the data in accordance with the statistical software used. The software used in this thesis is S-PLUS® version 7.0.6 (Insightful Corp., 2005) and S-PLUS Life Data Analysis (SPLIDA) version 6.8.1 (Meeker, 2006). SPLIDA is a collection of S-PLUS extensions for conducting analysis of reliability data. It is capable of analyzing censored life data, recurrence data, and the MCF (Meeker and Escobar, 2004, p. 7).

The refined ERO history data, represented in Appendix B, are formatted as a data object which contains vehicle failure times and failure origin within the observation start and end dates. The data object is created using the ERO history data, critical MTVR life dates, major unit MTVR usage rates, and an odometer reading imputation function, to produce the data frame of system or subsystem failure recurrence data.

III. ANALYSIS

This chapter presents both parametric and nonparametric statistical analyses of the MTVR data described in Chapter II. Before presenting these analyses, the usage profiles of MTVRs fielded in OIF are described, which provides useful insights to the analyses that follow.

A. OPERATIONAL USE AND PERFORMANCE

Starting with a sample of 456 MTVRs fielded in OIF during the timeframe of the thesis research, data review and refinement resulted in usable odometer readings for 378 of these vehicles. Analyzing these 378 MTVRs by variant and unit suggests different operational attributes that may affect the performance of MTVRs in the field.

For the reduced sample of 378 MTVRs the mean usage is 336 miles per month. A detailed breakdown of monthly usage, by variant and unit, is shown in Figure 6, Figure 7, and Table 8. The two basic cargo variant models, the Standard Bed and the Extended Bed, have similar profiles although there is greater sample variability among the Standard Bed vehicles. The Extended Bed, which is used in logistics organizations, is tasked to carry more cargo than the Standard Bed, and its median usage is about 100 miles per month greater than the Standard Bed. Regarding unit usage, the logistics unit (MLG) is highest, which is not surprising given that this unit’s mission is to provide logistics support throughout Al Anbar province. The headquarters unit (MHG) has the lowest monthly usage. The coefficient of variation for unit mean monthly vehicle usage, determined by dividing the standard deviation by the mean, indicates how evenly an organization is using their MTVRs. A lower value for the infantry division unit (DIV) and aircraft wing unit (MAW) indicates even usage, whereas a higher value exhibited by the logistics unit (MLG) indicates uneven usage.

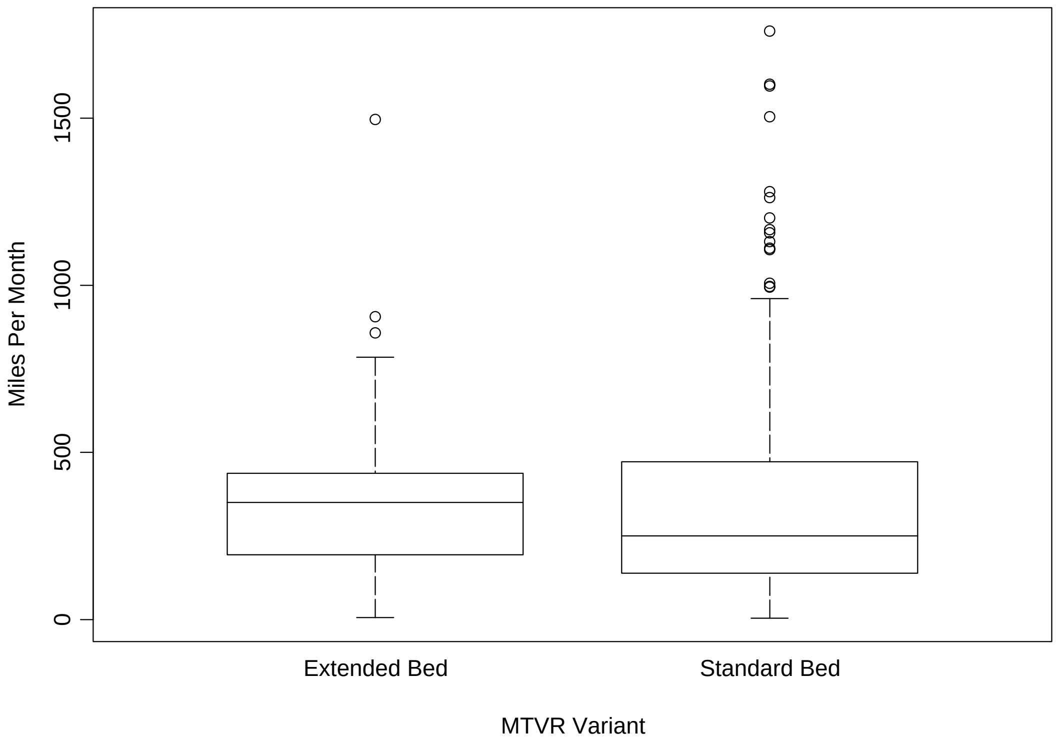

Figure 6. Boxplot of Monthly MTVR Usage by Variant. Center Lines in Boxes Represent Medians. Boxes Range from Lower to Upper Quartiles.

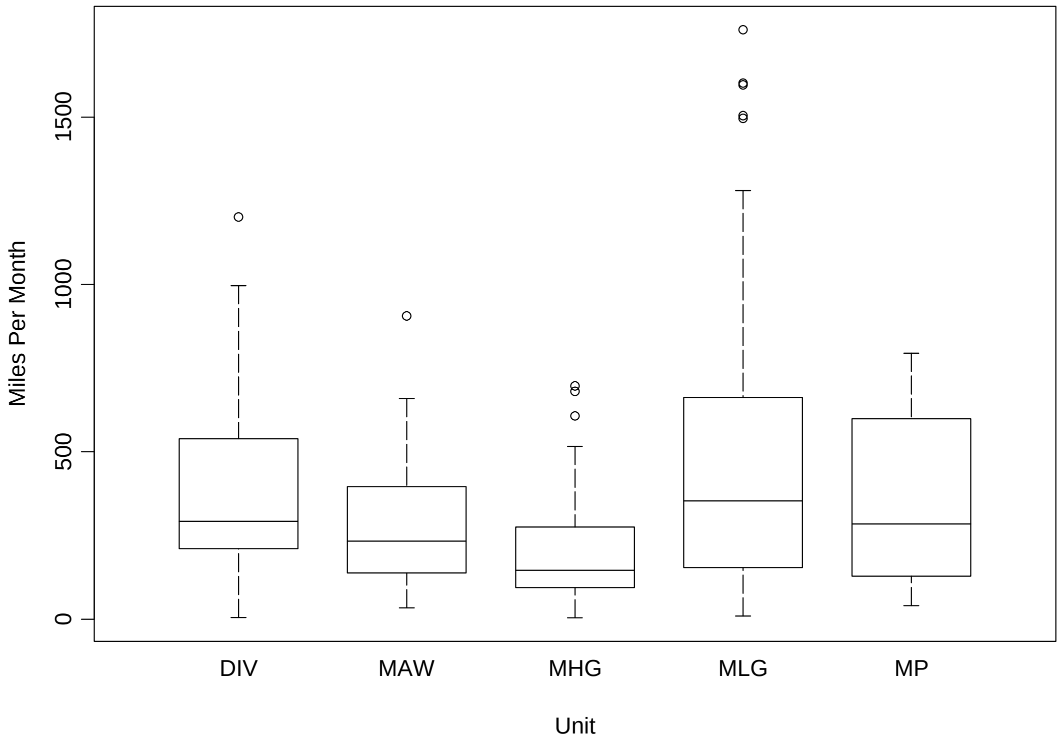

Figure 7. Boxplot of Monthly MTVR Usage by Unit. Center Lines in Boxes Represent Medians. Boxes Range from Lower to Upper Quartiles.

	Sample	**DIV**	**MAW**	**MHG**	**MLG**	**MP**
Mean	357	377	276	195	469	351
Median	269	293	233	147	353	284
Standard Deviation	302	243	186	155	408	248
Coefficient Of Variation	0.84	0.64	0.67	0.80	0.87	0.71

Table 8. Vehicle Monthly Usage Summary.

The frequency of system level failures in the two basic cargo variant models corresponds with their mean monthly usage. The Extended Bed produces 6.8 failures per vehicle with a mean monthly usage of 344 miles, while the Standard Bed produces 5.4 failures per vehicle with a mean monthly usage of 332 miles. For units, Figure 8 shows that the headquarters unit (MHG) and aircraft wing unit (MAW) have the highest failures per vehicle even though their unit usage is the lowest of the five units. The infantry division unit (DIV) has the second lowest failures per vehicle while having the second highest unit usage. These comparisons indicate a relationship between vehicle failures, usage levels, and the type of unit to which a vehicle is assigned.

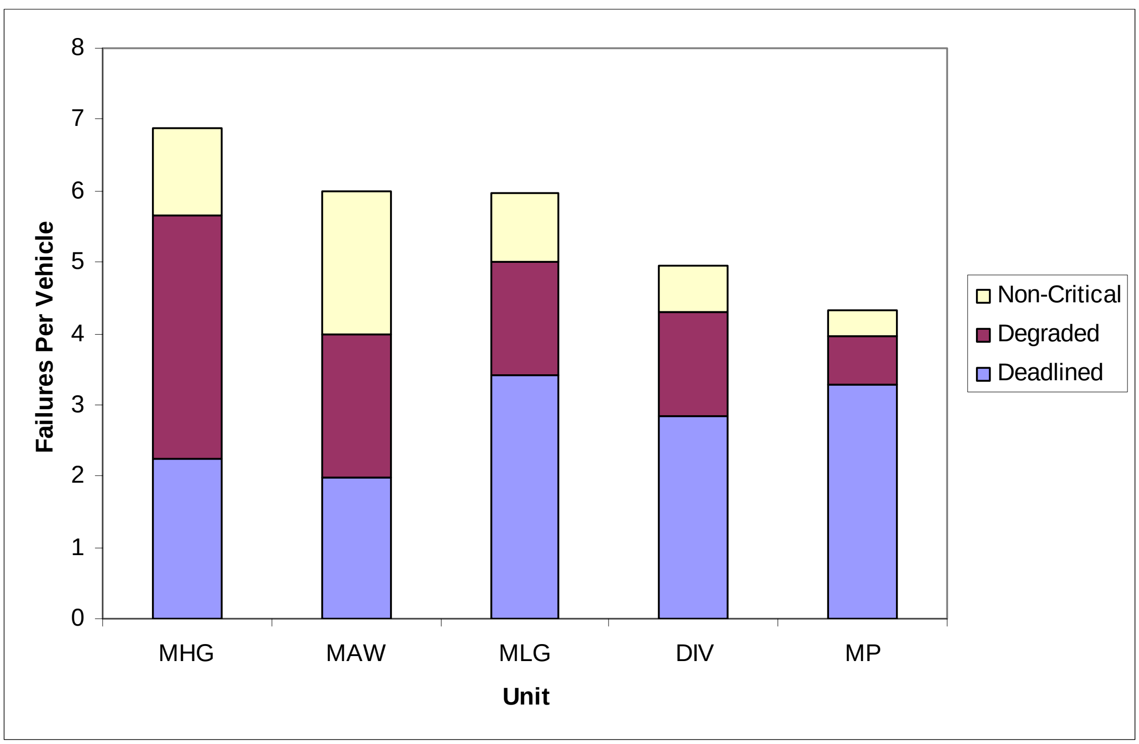

Figure 8. Failures Per Vehicle by Unit.

Reliability of the MTVR is determined from the reliability of each of its subsystems. While these subsystems vary in size, design, and purpose, each is affected by operational use and environmental factors. A Pareto chart of subsystem failures and deadlining failures is shown in Figure 9 and Figure 10, respectively. While the BODY subsystem contains the most failures, this subsystem is affected by numerous interim armor applications prior to the MAS, which inflate the BODY subsystem number of failures. This inflation is caused by interim armor applications being treated as unscheduled maintenance, when they should be treated as scheduled maintenance. The AXLE/SUSP subsystem comprises 22 percent of the system's failures and 23 percent of the system's deadlining failures. Moderate deadlining failure activity is shown in the ELEC subsystem (13 percent) and ENG subsystem (13 percent), and the remaining subsystems comprise less than 11 percent of the system's deadlining failures. While these charts provide an understanding of which subsystems are demanding the most maintenance and supply attention, individual subsystem performance determination should occur within the context of the total number of repair parts in each subsystem. As shown in Table 9, the FUEL, AXLE/SUSP, and ENG subsystems demand the most failure attention per subsystem part count, while the FUEL, COOL, and AXLE/SUSP subsystems demand the most deadlining failure attention per subsystem part count.

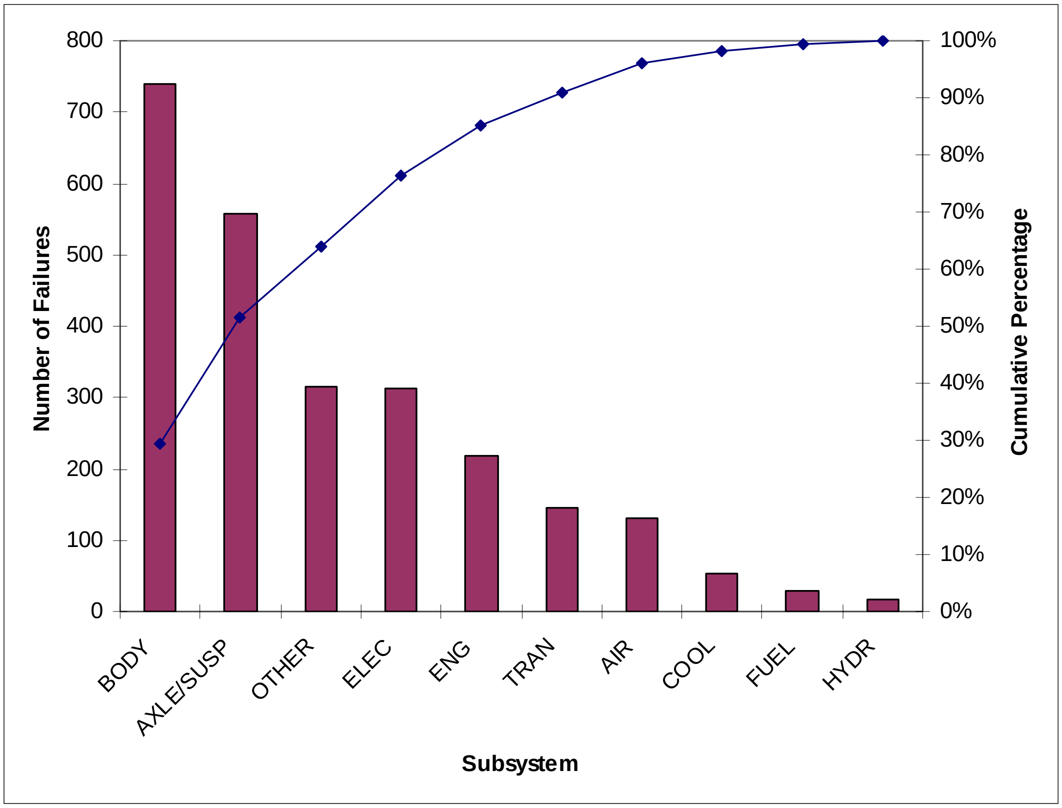

Figure 9. Pareto Chart of Failures by Subsystem.

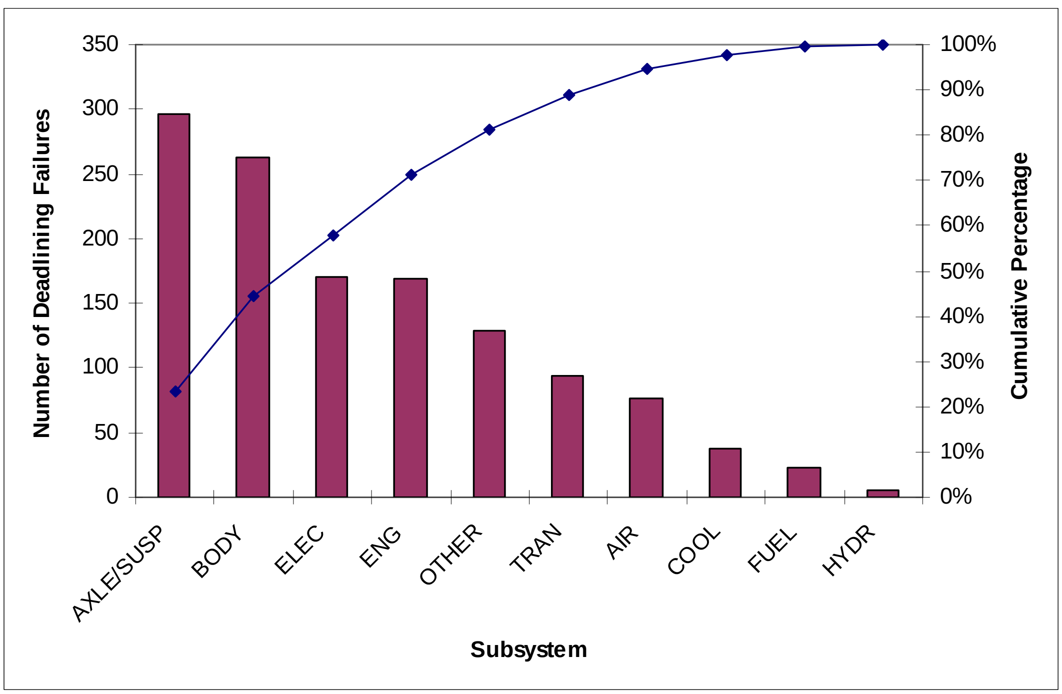

Figure 10. Pareto Chart of Deadlining Failures by Subsystem.

Subsystem	Number of Parts	Failures	Deadlining Failures	Failures Per Part	Deadlining Failures Per Part
FUEL	105	28	23	0.267	0.219
AXLE/SUSP	2848	558	296	0.196	0.104
ENG	1779	218	169	0.123	0.095
TRAN	1353	145	37	0.107	0.027
COOL	512	53	94	0.104	0.184
BODY	9100	739	170	0.081	0.019
ELEC	5769	312	263	0.054	0.046
OTHER	6301	315	76	0.050	0.012
AIR	3031	132	129	0.044	0.043
HYDR	3304	16	6	0.005	0.002

Table 9. Subsystem Part and Failure Comparison.

The AXLE/SUSP subsystem is further analyzed due to its high failure and deadlining failure activity. The Repair Part history data and MTVR IETM subsystem configuration and parts list enable a review of deadlining failures at the AXLE/SUSP subsystem's component level. Table 10 shows the results of this review. The Front Axle/Suspension and Rear Axle/Suspension components demand significant attention by producing high parts ordered per number of component parts. The Wheel and Tire Group, though, has the highest number of parts ordered per number of component parts. This is due to a large demand for the following repair parts: Pneumatic Tire (NSN 2610-01-334-2694), Plain Hexagon Nut (NSN 5310-01-492-5571), Wheel and Tire Assembly (NSN 2530-01-497-0440), and Metallic Hose Assembly (NSN 4720-01-480-3992).

Component	Number of Parts in Component	Percent of Total Parts in AXLE/SUSP Subsystem	Number of Parts Ordered for Component	Percent of Total Parts Ordered for AXLE/SUSP Subsystem
Front Axle/Suspension	1387	49	2343	53
Rear Axle/Suspension	757	27	1141	26
Automatic Breaking System	261	9	309	7
Steering System	229	8	151	3
Central Tire Inflation System	135	5	139	3
Wheel and Tire Group	79	3	373	8

Table 10. Summary of AXLE/SUSP Subsystem Component Performance for Deadlining Failures.

B. NONPARAMETRIC STATISTICAL METHODS

A cumulative plot of the number of failures versus the age of a system is the simplest reliability graph for a repairable system. The plot can be modified easily to match the given data or desired analysis. Failures can represent degrees of failure, subsystem failures, or carry a weight such as days deadlined or repair cost, and age can be replaced with chronological time, vehicle operational time (i.e., not deadlined), or miles driven. The plotted line represents the system performance over time, and categorizes the system performance as stable (constant slope), improving (decreasing slope), or worsening (increasing slope).

A determination of the average behavior of numerous systems is achieved by using the Mean Cumulative Function (MCF). The MCF is calculated as failure events occur for systems at a point in time, and manages truncation and censoring by focusing only on the observed systems. The MCF is defined as

$$MCF(t_0) = 0$$

$$MCF(t_k) = MCF(t_{k-1}) + \frac{w(t_k)}{N(t_k)}$$

where $t_0, t_1, ..., t_{k-1}, t_k$ represent increasing times of failure events from start time t_0 (MTVR fielding) to the k^{th} failure event, $w(t_k)$ is the weight associated with the failure event, and $N(t_k)$ is the number of MTVRs being observed at time t_k (Glosup, Heavlin, and Trindade, 2007). Unit weights $w(t_k) = 1$ are the most commonly used, so that $MCF(t)$ estimates the mean number of failures experienced by a unit up to time t. If costs (severity) of failures are measured then these can be used as weights, and $MCF(t)$ estimates the mean cost of failures up to time t. Table 11 illustrates the MCF calculation with unit weights ($w(t_k) = 1$).

Date Received In Shop	**Number of MTVRs Being Observed**	**Failures per MTVR**	**MCF**
1/15/2007	3	1/3	1/3
1/30/2007	3	1/3	2/3
2/10/2007	3	1/3	1
2/15/2007	2	1/2	3/2
2/28/2007	2	1/2	2
3/5/2007	1	1/1	3
3/10/2007	1	1/1	4

Table 11. Example of MCF Calculation.

The MCF is a nonparametric estimator of the population mean cumulative number of arrivals (or mean cumulative cost, depending on the weights used) for a typical unit. It does not assume any pre-specified functional form. Large-sample confidence intervals for the population MCF can be derived using well-known formulas. A detailed description of the statistical properties of the MCF and its underlying assumptions is given in Meeker and Escobar (1998).

MCF plots obtained with SPLIDA enable reliability analysis at the system, subsystem, variant, unit, and MAS armor status levels. The time factor in MCF plots can be based upon chronological time (Days), operational time (Net Days), miles driven (Miles), or net miles driven (Net Miles). While like time factors, such as Days and Net Days, produce similar plots, there is a difference between plots based upon time and miles driven. This difference is illustrated in Figure 11 and Figure 12. The MCF plot with Net Days has an increasing slope, indicating worsening performance as the systems age, while the MCF plot with Net Miles has a constant slope, indicating stable performance.

Because age of a mechanical system usually is best expressed in terms of usage, and because usage does not increase at times when a vehicle is deadlined, MCF plots are based on Net Miles in the remainder of the thesis. This determination is supported by strong coefficients of correlation between unit Net Miles and unit failures (0.90), and unit Net Miles and unit deadlining failures (0.87). The Days, Net Days, and Miles time factors do not have a strong coefficient of correlation in both failure categories like Net Miles does.

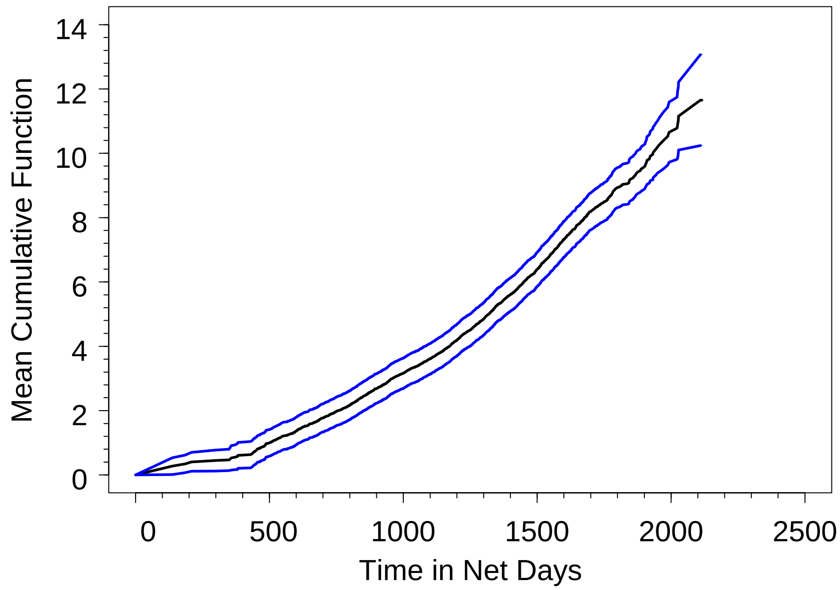

Figure 11. MTVR System MCF with 95 Percent Confidence Interval. Time is Measured in Net Days.

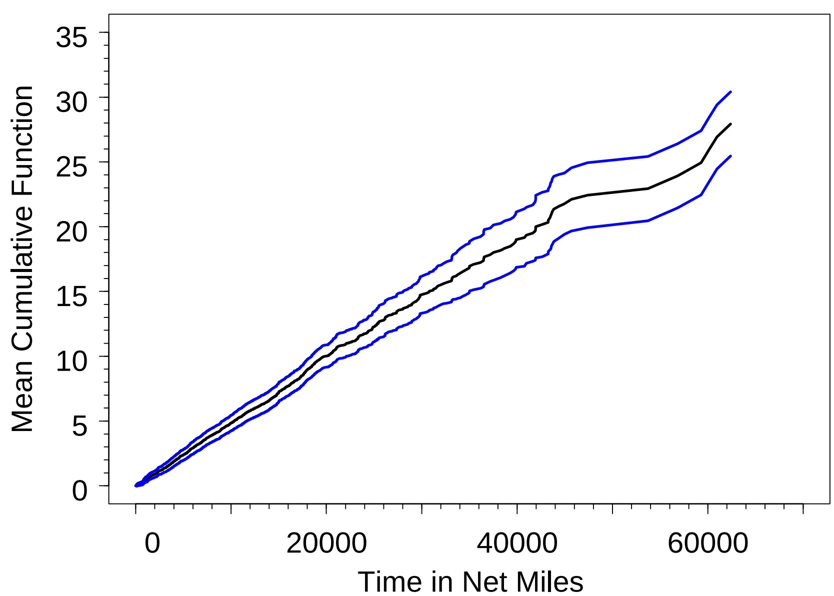

Figure 12. MTVR System MCF with 95 Percent Confidence Interval. Time is Measured in Net Miles.

Failure and deadlining failure MCF plots are produced for each unit in Figure 13 and Figure 14. The MCF plot of failures is noticeably different than the MCF plot of deadlining failures. Regarding MTVR failures, the MCF value for the headquarters unit (MHG) is the highest at any given time, while the logistics unit (MLG) maintains lower MCF values throughout. Table 12 shows unit failure MCF values at 10,000 and 20,000 Net Miles, along with the unit's mean monthly usage. When unit mean monthly usage is compared to the corresponding MTVR failure MCF value at 10,000 and 20,000 Net Miles, the resulting coefficients of correlation are -0.97. This analysis shows that there is a strong inverse relationship between unit usage and MTVR failure MCF values. A potential cause of this relationship is that units with lower usage rates have more opportunity to address failure events as they arise, causing more unscheduled maintenance events. Alternatively, units with high usage may defer or combine the handling of failures, causing less unscheduled maintenance events.

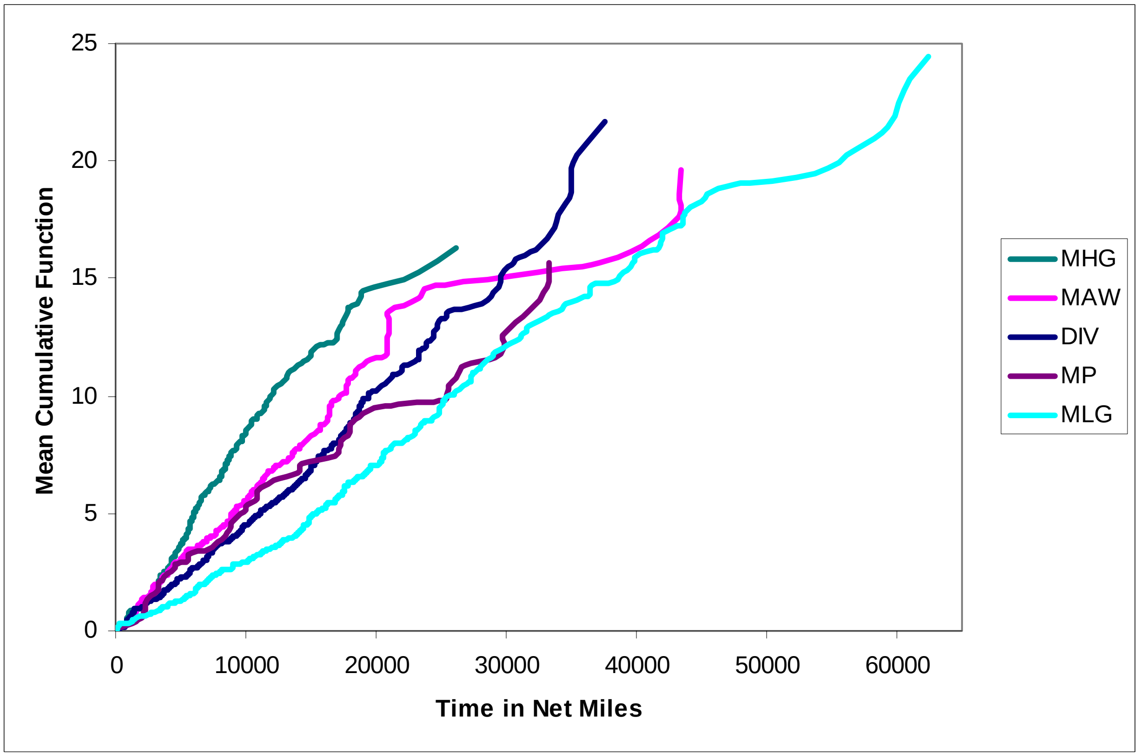

Figure 13. MTVR Failures MCF Plot by Unit.

Unit	Mean Monthly Usage	MCF Value at 10,000 Net Miles	MCF Value at 20,000 Net Miles
MHG	195	8.3	14.6
DIV	377	4.5	10.0
MAW	276	5.5	11.2
MLG	469	3.0	7.0
MP	351	5.2	9.3

Table 12. Comparison of Unit Usage and MTVR Failures MCF Values.

The noteworthy similarity between Figure 13 and Figure 14 is the logistics unit (MLG) MCF plot. Both depict the logistics unit (MLG) with the lowest MCF values per Net Miles, even though that unit has the highest mean usage. The infantry division unit (DIV) deadlining failure MCF plot shows the highest values beyond 20,000 Net Miles, with a clearly visible increasing slope MCF plot.

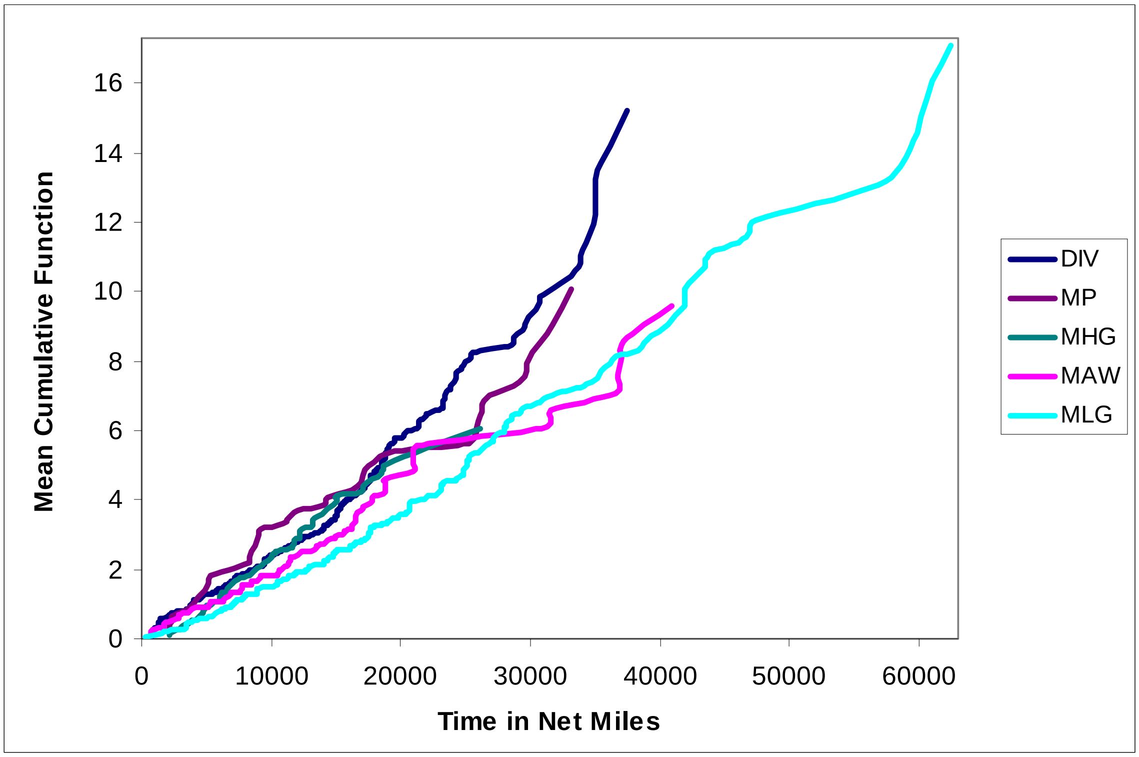

Figure 14. MTVR Deadlining Failures MCF Plot by Unit.

The Standard Bed and Extended Bed MTVR variants produce similar MCF values up to 30,000 Net Miles, as shown in Figure 15 and Figure 16. After this point, MCF values for the variants begin to diverge, with the Extended Bed MTVR produces the lowest failure and deadlining failure MCF values beyond 30,000 Net Miles. The Standard Bed with MAS Cab produces the highest deadlining failure MCF values beyond 30,000 Net Miles, with a slight increasing slope MCF plot that indicates worsening performance.

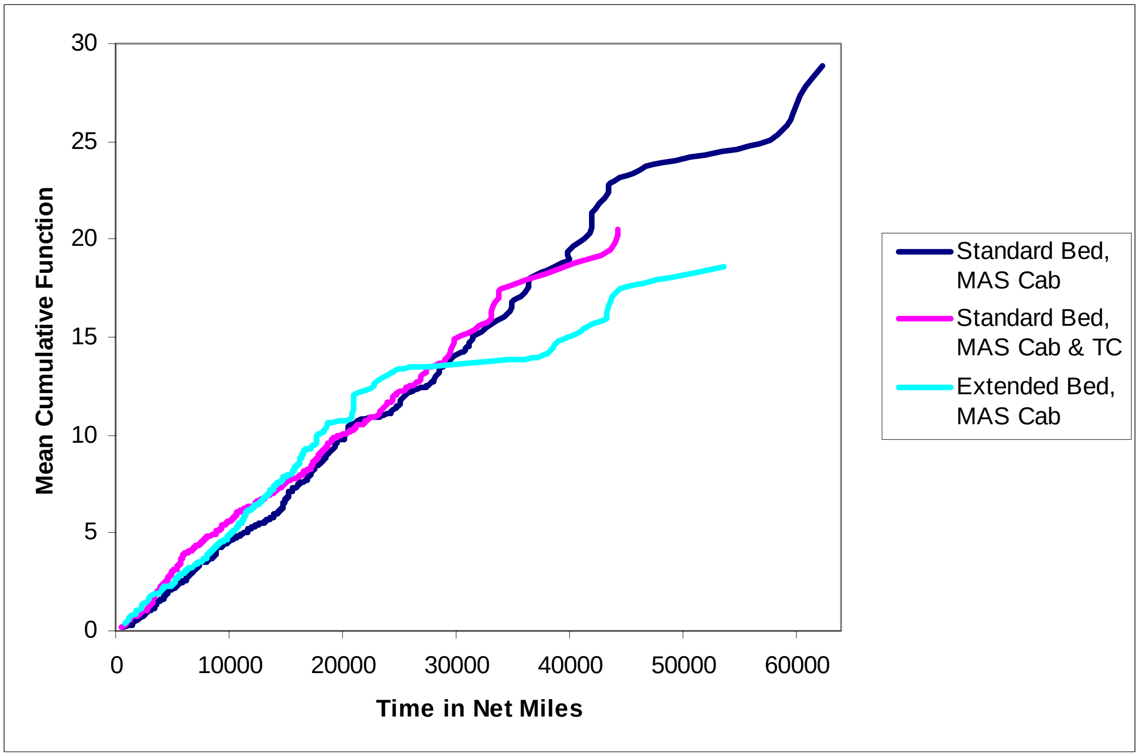

Figure 15. MTVR Failures MCF Plot by Variant.

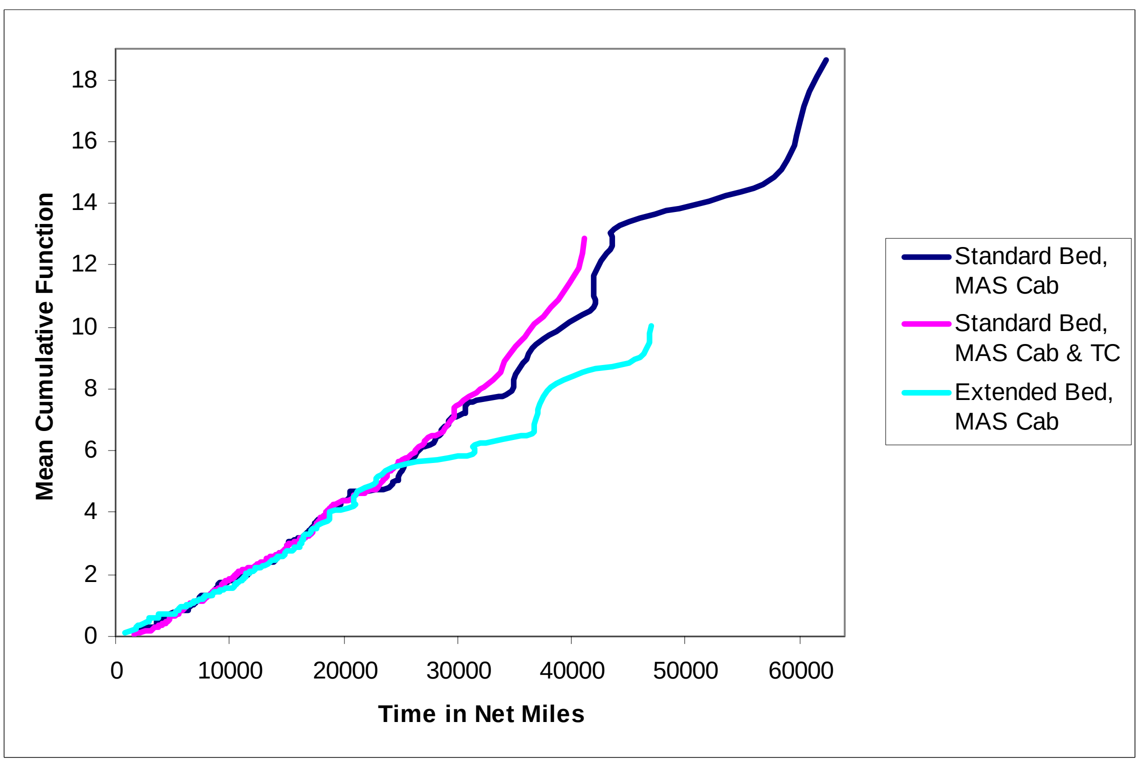

Figure 16. MTVR Deadlining Failures MCF Plot by Variant.

A comparison of MTVR deadlining failures before and after MAS armor installation demonstrates how the MTVR manages the additional weight of the MAS armor. A plot of the MCF values before MAS armor installation minus the MCF values after the MAS armor installation will provide this comparison. Figure 17 shows this comparison for each variant. If there is no change in MCF performance before and after MAS armor installation, the plotted line will follow the "0" value horizontal axis. Yet the comparative plots for the Standard Bed with MAS Cab and the Standard Bed with MAS Cab and Troop Carrier each show a negative slope line, identifying higher MCF values after MAS armor installation than before MAS armor installation. The variant that shows the greatest difference from before to after MAS armor installation is the Standard Bed with MAS Cab armor.

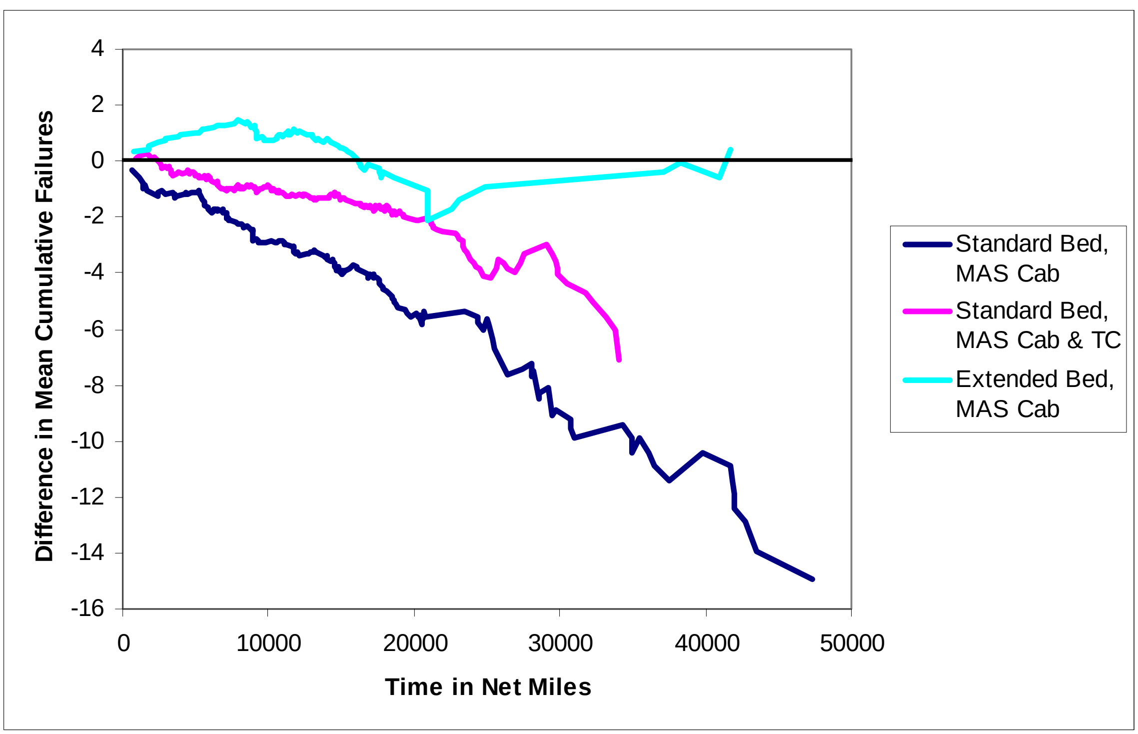

Figure 17. Difference in MCF for Deadlining Failures Before and After MAS Armor Installation by Variant.

The results of the MCF comparison of before and after MAS armor installation are further substantiated through the use of the sign test (Conover, 1999, p. 157). Assuming $N_{B,i} \sim Poisson(\tau_{B,i}, \lambda_B)$ and $N_{A,i} \sim Poisson(\tau_{A,i}, \lambda_A)$, where $N_{B,i}$ is the number of failures before MAS armor installation for vehicle i, $N_{A,i}$ is the number of failures after MAS installation for vehicle i, $\tau_{B,i}$ is the observed time before MAS installation for vehicle i, $\tau_{A,i}$ is the observed time after MAS installation for vehicle i, λ_B is the failure rate before MAS installation, and λ_A is the failure rate after MAS installation,

$$\hat{\lambda}_{B,i} = N_{B,i} / \tau_{B,i}$$

$$\hat{\lambda}_{A,i} = N_{A,i} / \tau_{A,i}$$

and

$$D_i = \hat{\lambda}_{A,i} - \hat{\lambda}_{B,i}$$

Letting $P(D_i > 0) = p$, a Sign Test (Conover, 1999) is conducted using the test statistic $S = \#\{D_i > 0\}$ where

$$H_0: \textit{ Failure rate does not increase with MAS } (p \leq .5)$$
$$H_1: \textit{ Failure rate does increase with MAS } (p > .5)$$

The sample size is $n = \#\{D_i \neq 0\}$. Table 13 shows the results of the Sign Test. In all cases, $p > .5$ and H_0 is rejected.

	$p = P(D_i > 0)$ **for Failures**	$p = P(D_i > 0)$ **for Deadlining Failures**
Standard Bed w/ MAS Cab	0.85	0.73
Standard Bed w/ MAS Cab & TC	0.75	0.65
Extended Bed w/ MAS Cab	0.68	0.57

Table 13. Sign Test Results for Failures and Deadlining Failures by Variant.

The AXLE/SUSP subsystem is further analyzed using MCF plots due to its high failure and deadlining failure activity. While an MCF plot of subsystem failures produces similar results for each variant, as shown in Figure 18, the MCF comparison of before MAS armor installation and after MAS armor installation clearly shows the different performance of the subsystem in each variant. Figure 19 shows that a higher MCF trend exists after MAS armor installation than before MAS armor installation for the Standard Bed with the MAS Cab armor kit. Deadlining failure MCF values in Figure 20 provide a slightly different result. The Standard Bed with MAS Cab and Troop Carrier shows worsening performance after 30,000 Net Miles, while the other variants show less severe degradation.

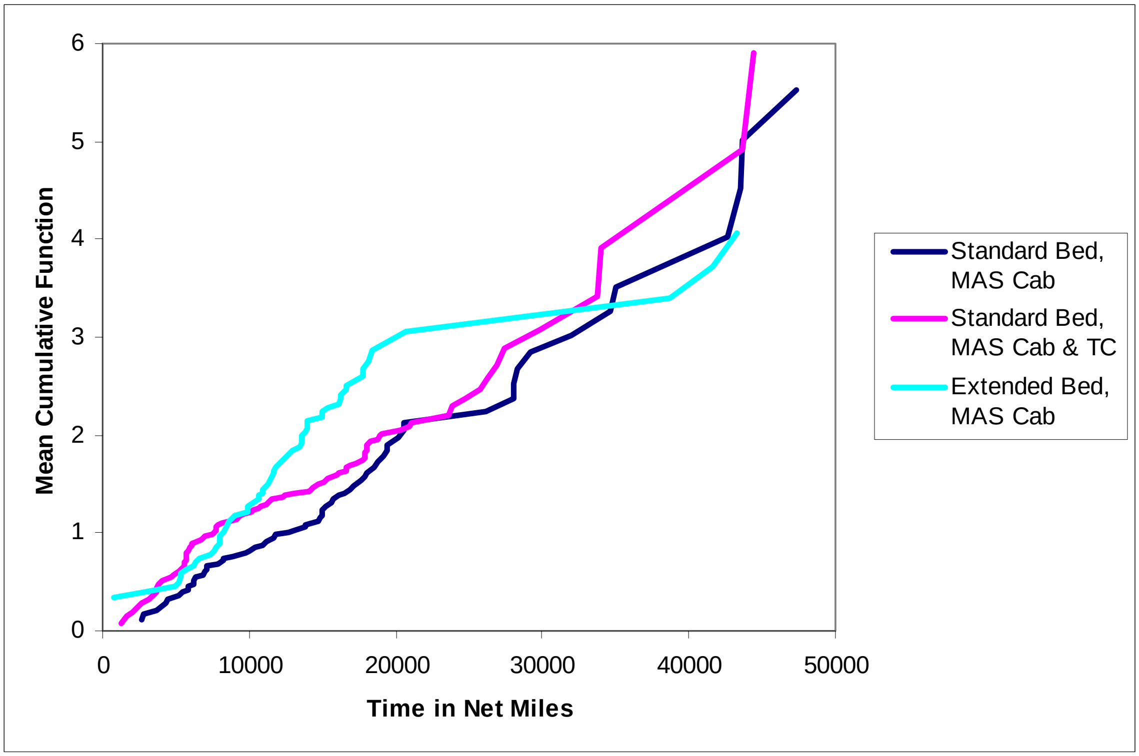

Figure 18. AXLE/SUSP Subsystem Failures MCF Plot by Variant.

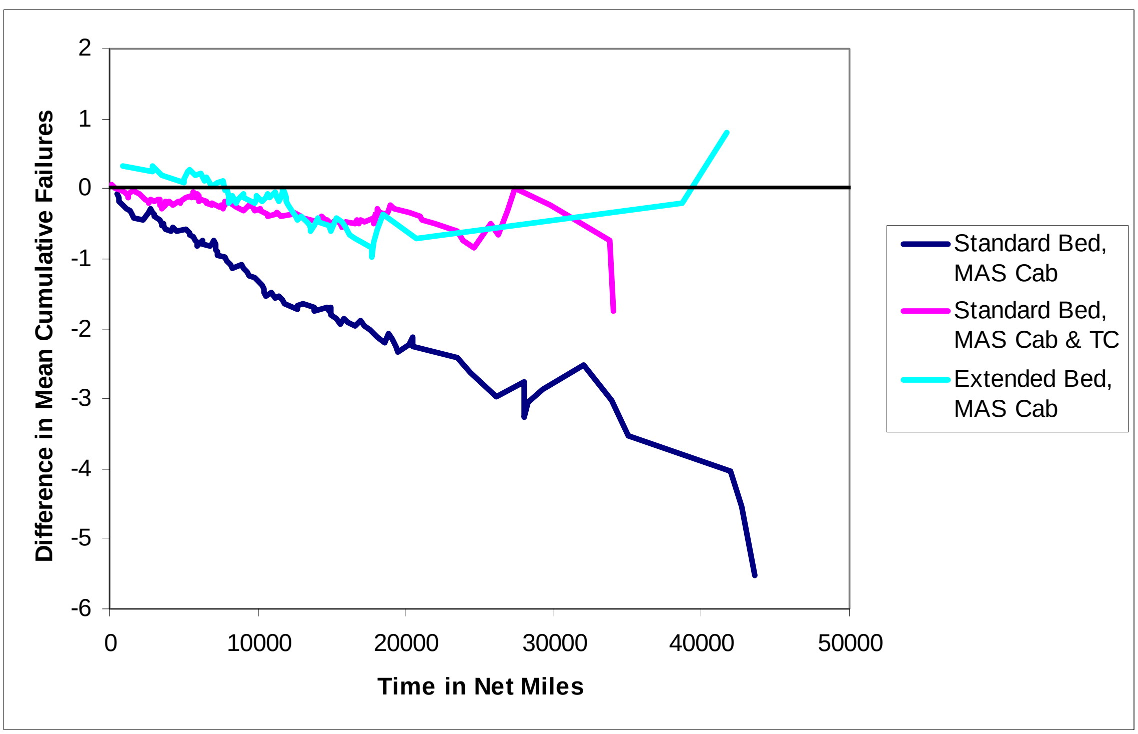

Figure 19. Difference in AXLE/SUSP Subsystem MCF for Failures Before and After MAS Armor Installation by Variant.

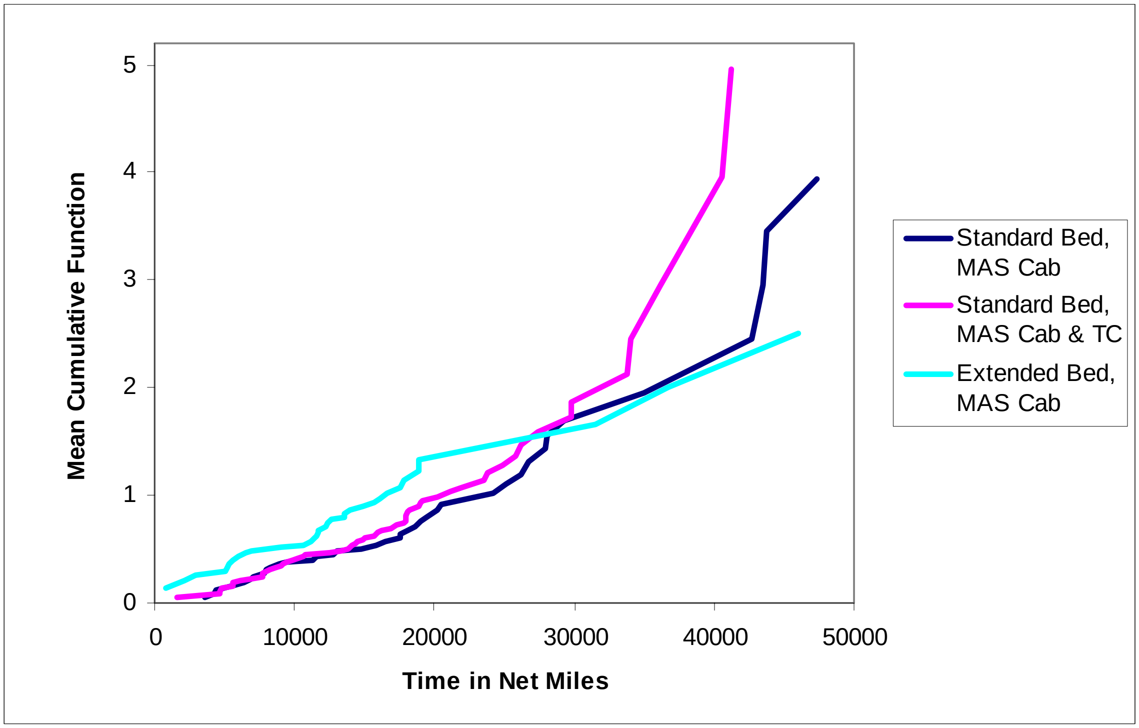

Figure 20. AXLE/SUSP Subsystem Deadlining Failures MCF Plot by Variant.

The MCF can be modified to incorporate a measure of weight, associated with the failure event, by using the failure event's number of days deadlined. The number of days deadlined for a failure event is affected by maintenance and supply activity. Assigning days deadlined to $w(t_k)$ in the MCF calculation will produce the cumulative lack of availability during the period of observation. This technique is applied at the system and AXLE/SUSP subsystem levels for each variant, with the results shown in Figure 21 and Figure 22. The weighted MCF plot in Figure 21 shows that the Standard Bed and Extended Bed variants diverge after approximately 30,000 Net Miles. Figure 22 also shows this divergence, but at a much earlier point in the period of observation.

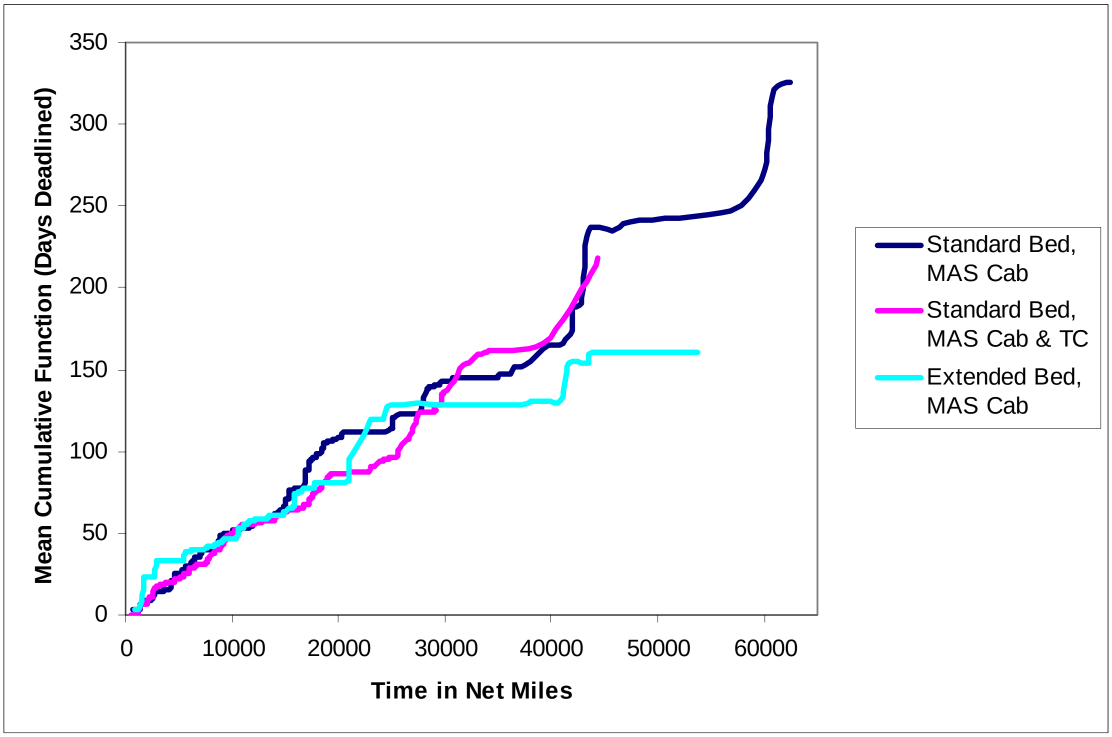

Figure 21. Deadlined Days Weighted MCF Plot by Variant.

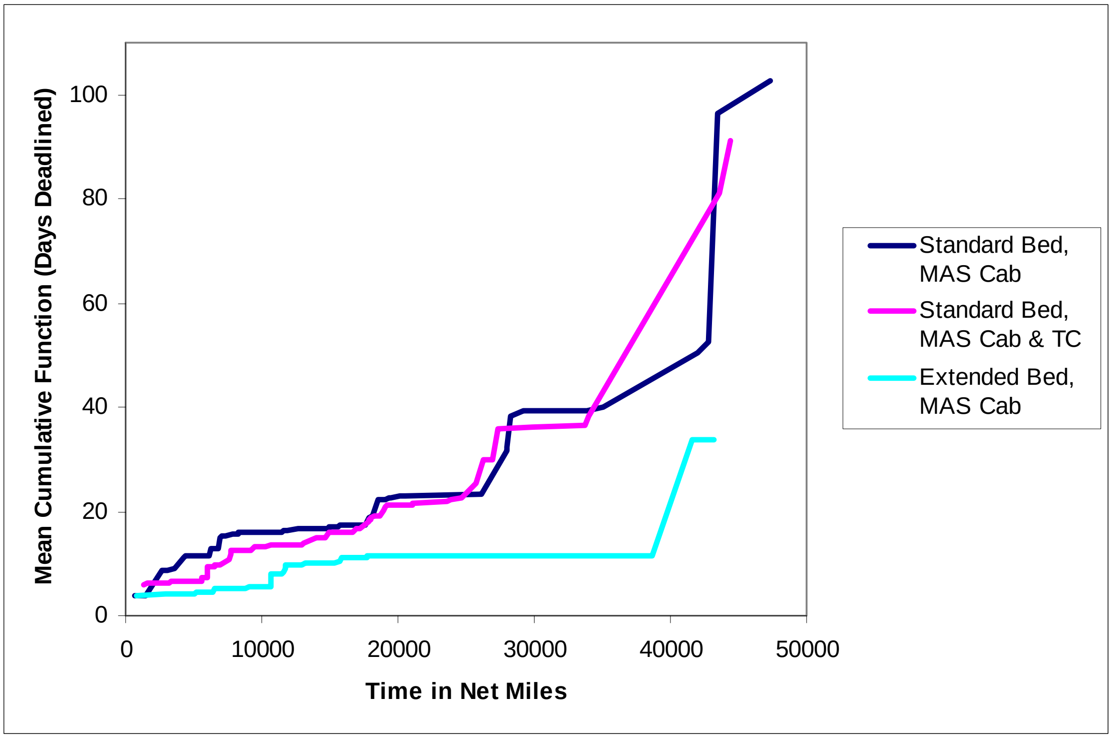

Figure 22. AXLE/SUSP Subsystem Deadlined Days Weighted MCF Plot by Variant.

C. PARAMETRIC STATISTICAL METHODS

The Poisson process is a common parametric model used for analyzing recurrence data. To use this model with recurrence data, the following conditions must be met:

- The number of failures at time $t = 0$ is zero, or $N(0) = 0$.
- The number of recurrences in disjoint time intervals are independent, referred to as having independent increments.
- The recurrence rate $\upsilon(t)$ is positive and $\mu(a,b) = E[N(a,b)] = \int_a^b \upsilon(u)du < \infty$, when $0 \le a < b < \infty$.

A nonhomogeneous Poisson process (NHPP) model is used when a nonconstant recurrence rate exists. When used in relation to the power-model recurrence rate,

$$\upsilon(t;\beta,\eta) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}, \quad \beta > 0, \quad \eta > 0.$$

Using the power-model recurrence rate, the mean cumulative number of recurrences over $(0,t]$ is $\mu(t;\beta,\eta) = \left(\frac{t}{\eta}\right)^{\beta}$. In instances when $\beta = 1$, a constant recurrence rate, the model becomes a homogeneous Poisson process (HPP) model (Meeker and Escobar, 1998, p. 406).

A Power Rule NHPP Maximum Likelihood Estimate (MLE) is calculated from non-parametric MCF plots using SPLIDA. The results of these calculations, for deadlining failures at the system level in the periods before MAS armor installation and after MAS armor installation, are shown in Table 14 and Table 15. Because β=1 is achieved, or closely achieved, in both Table 14 and Table 15 within the 95% confidence interval, the deadlining failure recurrence rate is modeled as a HPP.

		MLE	Standard Error	95% CI Lower	95% CI Upper
Standard Bed, MAS Cab	η	6436	1568	3362	9510
	β	1.03	0.15	0.73	1.33
Standard Bed, MAS Cab & TC	η	5819	1282	3306	8333
	β	1.01	0.14	0.74	1.28
Extended Bed, MAS Cab	η	5027	2192	732	9322
	β	0.84	0.19	0.46	1.21

Table 14. Power Rule NHPP MLE by Variant for Deadlining Failures Before MAS Armor Installation.

		MLE	Standard Error	95% CI Lower	95% CI Upper
Standard Bed, MAS Cab	η	2850	776	1329	4371
	β	1.10	0.12	0.87	1.33
Standard Bed, MAS Cab & TC	η	3931	1003	1966	5896
	β	1.11	0.13	0.85	1.36
Extended Bed, MAS Cab	η	3539	2363	-1093	8171
	β	1.00	0.28	0.46	1.54

Table 15. Power Rule NHPP MLE by Variant for Deadlining Failures After MAS Armor Installation.

The HPP model enables the use of a Poisson process with a constant recurrence rate. Furthermore, the HPP is a renewal process with inter-recurrence times that follow an exponential distribution (Meeker and Escobar, 1998, p. 408).

These characteristics enable the calculation of failure rate (λ) and Mean Time Between Failure (MTBF), where

- Failure rate (λ): The total number of failures within an item population, divided by the total time expended by that population, during a particular measurement interval under stated conditions (CNO, 2003, p. 57).
- Mean Time Between Failure (MTBF): For a particular interval, the total functional life of a population of an item divided by the total number of failures within the population (CNO, 2003, p. 62).

$$MTBF = \frac{1}{\lambda}$$

The η and β values in Table 14 and Table 15 are applied to determine the MTBF at a specified time, through

$$MTBF_t = \eta \Gamma \left(1 + \frac{1}{\beta} \right) \exp \left[\left(\frac{t}{\eta} \right)^{\beta} \right] P \left\{ G > \left(\frac{t}{\eta} \right)^{\beta} \right\}$$

where t is the time factor (Net Miles), Γ is the Gamma function, and G is a random variable having a standard gamma distribution with shape parameter $1/\beta$. This relationship is derived in Appendix G. Figure 23 shows a modified MTBF plot, for Mean Miles Between Deadlining Failure, for the period after MAS armor installation. The Extended Bed with MAS Cab armor shows better MTBF performance, potentially because of its mission and assigned units. These units are primarily the MAW and MLG, with missions that utilize hard surface roads over greater distances. When compared to the Mean Miles Between Operational Failure reliability MOE, represented by horizontal black dashed lines, each variant is below the

4,000 mile objective. Additionally, the Standard Bed with MAS Cab armor approaches and surpasses the 2,000 mile minimum beyond 50,000 Net Miles.

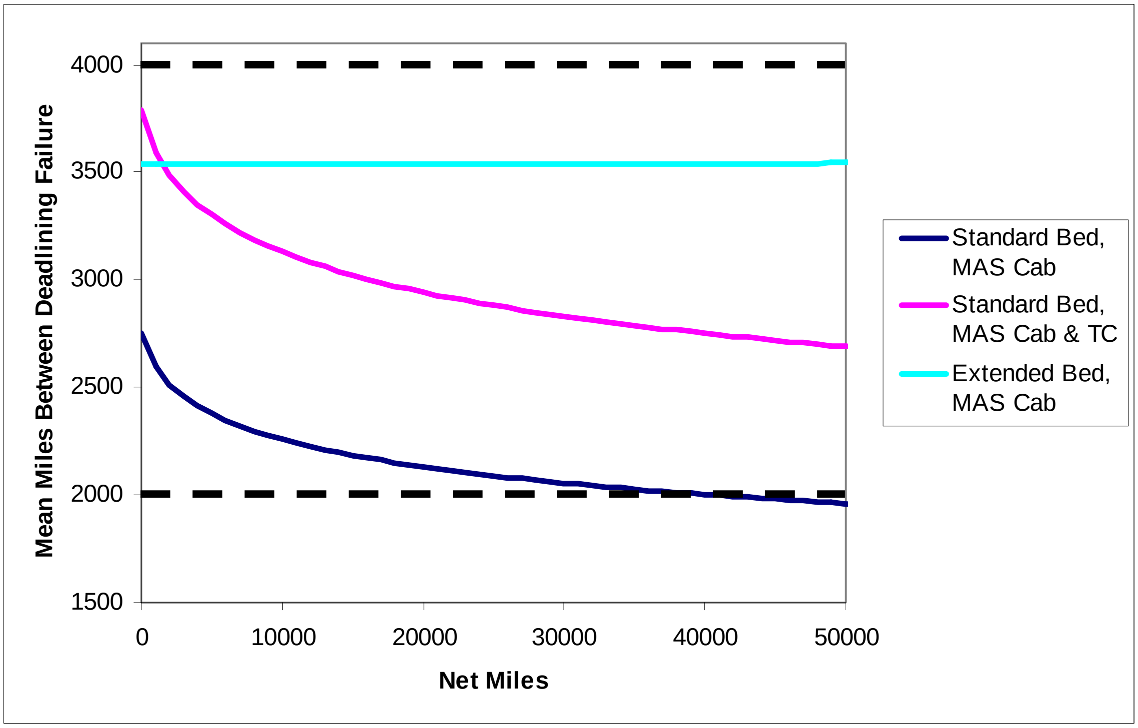

Figure 23. Mean Miles Between Deadlining Failure by Variant, as Usage Varies, After MAS Armor Installation.

Estimates of failure rate and MTBF are also determined for specific time intervals using the assumptions of the HPP. While the time interval can be delimited by a specified date or miles driven, this analysis uses the period before MAS armor installation and the period after MAS armor installation to estimate failure rate and MTBF over Net Miles driven. Table 16 shows an increase in each variant's λ, from the before to after MAS armor installation periods, by 162 percent, 76 percent, and 82 percent, respectively. Likewise, the MTBF in Figure 24 shows a decrease from the before to after MAS armor installation periods. It is noted that the Standard Bed with MAS Cab armor vehicles go from the best performance before the MAS armor installation, to the worst performance after MAS armor installation. The Mean Miles Between Operational Failure reliability MOE, represented by horizontal black dashed lines, is again compared to each variant's performance. While all variants are above the 4,000 mile objective in the period before MAS armor installation, each variant is below that MOE after MAS armor installation. The Standard Bed with MAS Cab armor is the variant closest to the 2,000 mile minimum.

	λ (Deadlining Failures Per 10,000 Net Miles)	
	Before MAS Install	**After MAS Install**
Standard Bed, MAS Cab	1.52	4.00
Standard Bed, MAS Cab & TC	1.81	3.19
Extended Bed, MAS Cab	1.64	2.99

Table 16. Deadline Failure Rates by Variant for the Before and After MAS Armor Installation Periods.

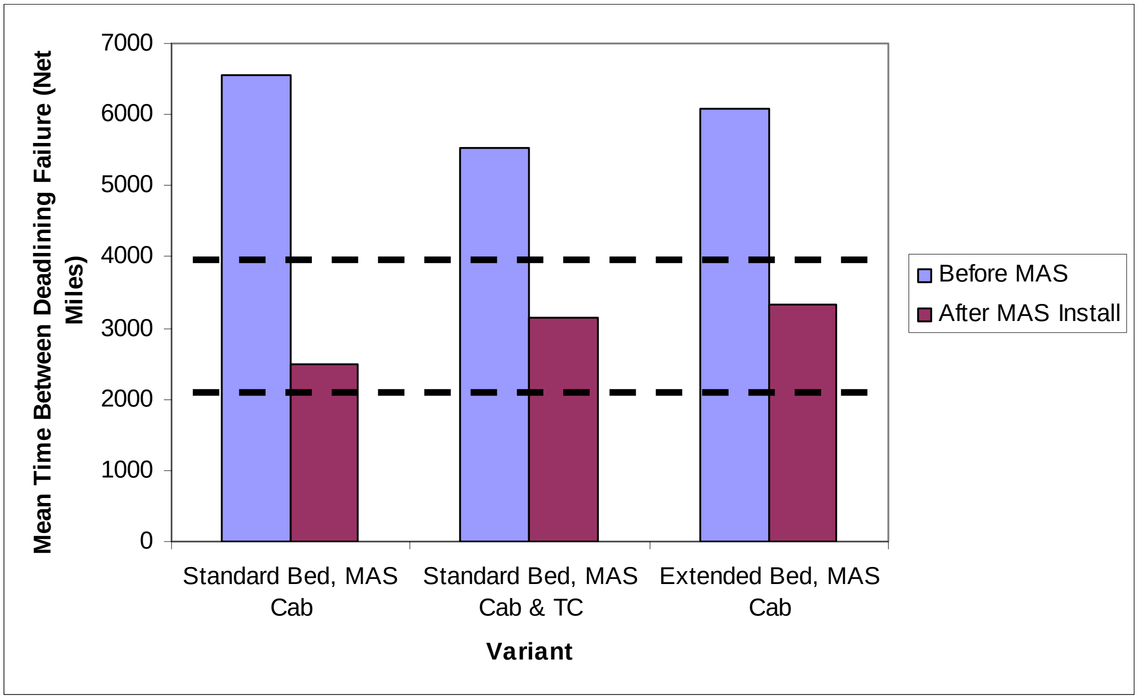

Figure 24. Mean Miles Between Deadlining Failure by Variant for the Before and After MAS Armor Installation Periods.

The HPP characteristics of the failure event recurrence data are further analyzed with a generalized linear model (GLM). A GLM allows for the incorporation of non-normal response variable distributions that are members of the exponential family (Montgomery, Peck, and Vining, 2001, p. 443). This relates to the MTVR failure event recurrence data following the HPP model. Poisson regression is used to model the relationship between failure events and the predominant predictor variables in this study, which are the MTVR time factor, variant, unit, and armor status. For the purpose of this analysis, another predictor variable used is the vehicle serial number, which is a blocking factor in the sense that two measurements are obtained for each vehicle in the analysis: one without MAS armor and one with MAS armor.

A fitted Poisson regression model for determining deadline failure rate and the mean time between deadlining failure, for the time periods before and after MAS armor installation, is presented below. The time factor used is Net Miles, and the vehicle sample used to generate this fitted model consists of the 378 MTVRs with useable odometer readings. The model takes the following form:

$$\log(\lambda) = \beta_0 + (\delta_2 u_2 + ... + \delta_5 u_5) + \gamma v + \sigma a + (\omega_2 u_2 v + ... + \omega_5 u_5 v) \\ + \sum_{j=2}^{k} \tau_j s_j + \log(\mathit{Net\ Miles})$$

where λ is the deadline failure rate, β_0 is the intercept, δ_i is the coefficient for unit u_i, γ is the coefficient for variant v (either Standard Bed or Extended Bed), σ is the coefficient for armored $(a = 0 \Rightarrow \text{ no MAS}, a = 1 \Rightarrow \text{ MAS})$, ω_i is the coefficient for unit u_i of variant v, τ_j is the coefficient for vehicle serial number s, and $\mathit{Net\ Miles}$ is the number of Net Miles during the respective vehicle's time period. This model is the result of first fitting a full set of interactions involving unit, variant, and armoring and then using backward elimination to remove insignificant predictors. The fitted model's coefficient values are shown in Table 17.

Coefficient	Variable	Value
β_0	Intercept	-27.023
δ_2	MAW, Standard Bed	18.542
δ_3	MHG, Standard Bed	19.511
δ_4	MLG, Standard Bed	18.757
δ_5	MP, Standard Bed	18.451
γ	Variant	18.691
σ	Armored	0.922
ω_2	MAW, Extended Bed	-18.976
ω_3	MHG, Extended Bed	N/A
ω_4	MLG, Extended Bed	-19.875
ω_5	MP, Extended Bed	N/A

Table 17. Poisson Regression Fitted Model Coefficient Values. N/A implies that the interaction is not estimable.

Because the Armored variable does not interact with any other variable, it is possible to identify a single, concise measure of the deadline failure rate difference in the periods before and after MAS armor installation. The Armored variable coefficient (σ) has an estimated value of 0.922 (0.104 standard error), with a 95 percent confidence interval of [0.835, 1.01]. For a given vehicle, the ratio of expected deadlining failures per 10,000 miles after MAS armor installation to the expected value before MAS armor installation is given by the following:

$$\left(\frac{\lambda_{After\ MAS}}{\lambda_{Before\ MAS}}\right) = e^{\sigma} = e^{.922} = 2.51,$$

with a 95 percent confidence interval of [2.30, 2.74]. The reciprocal of this ratio relates to MTBF, and is .398 with a 95 percent confidence interval of [.365, .434]. This ratio represents the percent reduction in MTBF from the period before MAS armor installation to the period after MAS armor installation. Deadlining failures arrive much sooner on average after MAS armor installation than before.

The Poisson regression model presented above uses the individual vehicles as blocking factors, so that it takes the form of a paired comparison of the before and after armoring states. The model is useful for estimating change as a vehicle transitions from an unarmored state to an armored state. To obtain estimates of reliability metrics in these two states, under an assumption that the MTVRs in the analysis are like a random sample of MTVRs used in OIF, we fit Poisson regression models separately to the unarmored and armored vehicle data, omitting the vehicle serial number as a predictor variable.

When the periods before and after MAS armor installation are separately modeled using Poisson regression, the following fitted model is obtained, again using a backward elimination procedure starting with a full model which includes unit, variant, and the interaction between unit and variant:

$$\log(\lambda) = \beta_0 + (\gamma_2 v_2 + ... + \gamma_4 v_4) + \log(Net\ Miles) ,$$

where λ is the deadline failure rate, β_0 is the intercept, γ_i is the coefficient for variant v_i, and $Net\ Miles$ is the number of Net Miles during the before or after MAS armor installation time period. The fitted model coefficient values are shown in Table 18.

Coefficient	Variable	Value Before MAS Install	Value After MAS Install
β_0	Intercept	-8.776 (0.101)	-7.931 (0.069)
γ_2	Standard Bed with Winch	0.485 (0.186)	0.226 (0.153)
γ_3	Extended Bed	-0.217 (0.251)	-0.366 (0.182)
γ_4	Extended Bed with Winch	0.306 (0.251)	-0.241 (0.267)

Table 18. Poisson Regression Fitted Model Coefficients for Before and After MAS Armor Installation Periods. Numbers in Parentheses are Standard Errors.

The fitted model is used to produce the deadline failure rate for the periods before and after MAS armor installation, as shown in Table 19. The rate increases for each variant in the period after MAS armor installation, with the largest increase for the Standard Bed variant (133 percent increase) and the smallest increase for the Extended Bed with Winch variant (35 percent increase). Mean miles between deadlining failures are calculated using the deadline failure rate, and are shown by variant in Table 20. These results are similar to those presented in Figure 24. In the period after MAS armor installation, the Standard Bed variant has mean miles between deadlining failure values just above the 2,000 mile reliability MOE minimum, while the Extended Bed variant has values close to the 4,000 mile reliability MOE objective. A result not observed previously in this thesis is the different performance of variants with the winch assembly. For both the Standard Bed variant and the Extended Bed variant, the mean miles between deadlining failures is less for the variant with a winch. A potential cause of this difference is the increased usage of variants with a winch, due to their ability to perform self recovery and recovery of HMMWVs on tactical convoys.

	Period Before MAS Armor Install			Period After MAS Armor Install		
Variant	**Deadline Failure Rate (per 10,000 Net Miles)**	**95% CI Lower**	**95% CI Upper**	**Deadline Failure Rate (per 10,000 Net Miles)**	**95% CI Lower**	**95% CI Upper**
Standard Bed	1.54	1.26	1.88	3.60	3.14	4.12
Standard Bed with Winch	2.51	1.84	3.41	4.51	3.44	5.91
Extended Bed	1.24	0.79	1.95	2.49	1.79	3.48
Extended Bed with Winch	2.10	1.33	3.30	2.83	1.70	4.70

Table 19. Deadline Failure Rates, Per 10,000 Net Miles, by Variant for the Periods Before and After MAS Armor Installation.

	Period Before MAS Armor Install			Period After MAS Armor Install		
Variant	**Mean Miles Between Deadline Failure**	**95% CI Lower**	**95% CI Upper**	**Mean Miles Between Deadline Failure**	**95% CI Lower**	**95% CI Upper**
Standard Bed	6478	5307	7906	2781	2430	3184
Standard Bed with Winch	3987	2930	5426	2219	1692	2909
Extended Bed	8044	5116	12647	4009	2873	5596
Extended Bed with Winch	4768	3033	7498	3539	2127	5891

Table 20. Mean Miles Between Deadline Failure by Variant for the Periods Before and After MAS Armor Installation.

IV. CONCLUSIONS AND RECOMMENDATIONS

The foundation of all analysis and modeling in this thesis is a comprehensive database of MTVR maintenance and supply requirements. Identification and refinement of the essential data elements in this database at an early stage was necessary to provide accurate analysis and modeling. The efficient processing of MDR data queries aided in creating the database, but improving the poor quality of MIMMS AIS data demanded more time than any other aspect of this thesis research. MIMMS AIS data is not directly suited for reliability analysis and modeling. This stems from the lack of control over user input in many of the essential data elements, and must be changed if future maintenance information systems are to be used for reliability analysis and modeling. Accurate data collection is the foundation of proper readiness reporting in the Marine Corps. This understanding must expand to include data collection in support of reliability analysis and modeling.

The sample size and 37 month period of observation met all of the thesis' analysis and modeling requirements. Multiple variants, units, and subsystems could not have been as thoroughly analyzed if a smaller sample had been taken. Yet care must be taken with a large sample. Vehicle observation start dates are managed based upon the type of analysis being conducted. Specifically, sample MTVRs that enter the period of observation at MAS armoring are not included in system and subsystem analysis and modeling because those vehicles, being new to the OIF environment, will degrade the accuracy of the results. Understanding the limitations of the data sample and the constraints of the analytical methods facilitates accurate results.

The results of operational use and performance provide an understanding that is further refined by non-parametric and parametric statistical methods. MTVR usage, measured in odometer miles (Net Miles), is used to capture vehicle age. System reliability analysis must be based upon the system's predominant age factor, whether it is rounds fired, hours operated, or miles driven. Reliability estimates are not useful if the appropriate age factor is not used.

Operational analysis shows that unit MTVR usage is uneven. Measures that could be taken to provide better balance and sustainment of the OIF MTVR fleet are:

- The logistics unit (MLG), which has the highest coefficient of variation for vehicle usage, should conduct an internal balancing of MTVRs based upon usage.
- The infantry division unit (DIV), which has the largest quantity of MTVRs and the second highest mean usage, should selectively exchange MTVRs with the aircraft wing unit (MAW) and headquarters unit (MHG), which have the lowest mean usage.
- Rotate Standard Bed MTVRs with greater than 30,000 miles. This measure is based upon the 2,000 Mean Miles Between Operational Failure minimum reliability MOE, the Mean Miles Between Deadlining Failure plot and graph in Figure 23 and Figure 24, and the Poisson regression model output in Table 20.
- Rotate Extended Bed MTVRs with greater than 40,000 miles. This measure is based upon the 2,000 Mean Miles Between Operational Failure minimum reliability MOE, the Mean Miles Between Deadlining Failure graph in Figure 24, and the Poisson regression model output in Table 20.

The unit MTVR usage identified in this thesis also can be used to refine OIF Equipment Density Lists (EDL) and established Tables of Organization and Equipment (TO&E). An alternate measure to balancing unit quantities would be to reduce MTVR EDL quantities in units with low usage rates. Similarly, future TO&E reviews can incorporate OIF usage rates into decisions to increase or decrease MTVR quantities in unit TO&Es.

Preventive Maintenance should provide appropriate attention to the systems and subsystems that are generating the most failures. For the OIF MTVRs, the following summary is provided in order focus Preventive Maintenance efforts:

- Poor or degrading reliability is a cause for concern in the infantry division unit (DIV) Standard Bed variants with MAS Cab armor, infantry division unit (DIV) Standard Bed variants with MAS Cab and Troop Carrier armor, and the AXLE/SUSP subsystem in Standard Bed variants with MAS Cab and Troop Carrier armor.
- The subsystems that are demanding the most maintenance attention, excluding the BODY subsystem, are the AXLE/SUSP, ELEC, and ENG subsystems. The FUEL and COOL subsystems are also demanding attention based upon their high deadlining failure per subsystem part ratio.
- Good reliability results are shown in the logistics unit (MLG) Extended Bed variants with MAS Cab armor, aircraft wing unit (MAW) Extended Bed variants with MAS Cab armor, and AXLE/SUSP subsystem in Extended Bed variants with MAS Cab armor.

The use of the NHPP model and the HPP model must be carefully determined for each aspect of the system being analyzed (i.e., variant, subsystem). Stochastic models for determining equipment reliability must be periodically compared with current equipment reliability data to ensure model assumptions are accurate. This concept applies to the TLCM-AT data models and simulation. Once Verification, Validation, and Accreditation (VV&A) is accomplished, TLCM-AT must be periodically compared with the actual reliability performance of the equipment it is modeling. This will sustain the accuracy of, and reliance upon, stochastic modeling for equipment life cycle management and assessment.

The best application of failure rate and MTBF is over as small an interval as possible (e.g., monthly is better than yearly). In the OIF MTVR sample, the deadlining failure rate is higher for each variant in the period after MAS armor installation than in the period before MAS armor installation. Specifically, and as shown in Table 16 using the HPP with deadline failure event recurrence data, the percent increase for each variant is:

- Standard Bed with MAS Cab armor: 162 percent
- Standard Bed with MAS Cab and Troop Carrier armor: 76 percent
- Extended Bed with MAS Cab armor: 82 percent

The trend of increasing deadline failure rates, and decreasing MTBF, is further validated in the Poisson regression modeling. The Poisson regression model results show that the MTVR cargo variant deadline failure rate is 2.51 times higher, and the MTBF is 39.8 percent lower, in the period after MAS armor installation than in the period before MAS armor installation. Separate Poisson regression modeling of the periods before and after MAS armor installation further support these results and the results found throughout the thesis' analysis. To summarize these results, the Standard Bed variant has the largest reliability degradation during the period of observation, and is approaching the minimum acceptable reliability MOE, while the Extended Bed variant has a reliability degradation that is acceptable within the established reliability MOEs.

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APPENDIX A

A. MTVR SPECIFICATIONS

- Cargo body: 14 ft (standard bed), 20 ft (extended bed)
- Curb Weight (un-armored): 27800 - 31069 lbs
- Gross Vehicle Weight Rating: 57800 - 61178 lbs
- Maximum speed: 65 mph
- Self-recovery winch: 20000 lbs
- Engine: Caterpillar C-12, 425 horsepower
- Transmission: Allison HD4070P 7-speed automatic
- Axles: Rockwell SVI 5MR
- Suspension: Oshkosh TAK-4 independent suspension

B. MTVR RELIABILITY MEASURES OF EFFECTIVENESS

- Mean Miles Between Operational Failures: 2000 miles (minimum), 4000 miles (objective)
- Probability of completing a 200 mile mission without mission failure: 0.90 (minimum), 0.95 (objective)
- Achieved availability: 0.89 (minimum), 0.90 (objective)
- Mean Time To Repair (MTTR): Organizational - 3 hours (minimum), Intermediate - 5 hours (minimum)
- Mean Miles Between Preventive Maintenance: 1800 miles (minimum), 3600 miles (objective)
- Mean Time To Perform Preventive Maintenance: less than 3 hours
- Maintenance Ratio (hours/operational miles): 0.01375 (minimum), 0.011 (objective)
- Service Life: 0.70 probability of completing 77000 miles (minimum) during its estimated 22 year service life without replacement of a major

component, e.g., engine, transmission, cooling system, electrical system, etc. (objective).

C. MTVR ARMOR SYSTEM SPECIFICATIONS

- Weight: 10,500 lbs (cab and troop carrier)
- Level I armor (permanent modification)
- Integrated cab armor system
- Armored rear troop carrier
- Ballistic glass
- Air conditioning system
- Machine gun mount
- V-shape belly pan and wheel zone deflectors
- Upgraded front suspension

D. MTVR SUBSYSTEMS

- AIR: Air system and intake air assembly
- AXLE/SUSP: Front and rear axle, suspension, wheel and tire group, ABS group, CTIS system, and steering system
- BODY: Armor, cab, cargo body group, cargo body mounting group, cargo body seat group, cargo cover camo kit group, data plate group, frame, sheet metal, and troop ladder group
- COOL: Cooling system
- ELEC: Electrical system
- ENG: Engine and exhaust system
- FUEL: Fuel system
- HYDR: Hydraulic group
- OTHER: Bulk items, options group, and repair kits
- TRAN: Propshaft, transfer case, and transmission

APPENDIX B

SAMPLE OF ERO HISTORY DATA

SN	ID	UNIT	ERO	SCHED	LEVEL	EVAC	DEF	SUBSYSTEM	CAT	DRIS	DLM2	DCLOSE	METER	USE MTR	MDD/L	PRI
590817	10629A	MLG	HI211	N	2		K34	ELEC	X	6/11/2004		8/20/2004	15823		0	5
590817	10629A	MLG	HI255	N	2		N12	BODY	X	9/8/2004		12/6/2004	23000		0	5
590817	10629A	MLG	XRM79	Y	2		I67	BODY	N	1/14/2006		3/24/2006	22185		0	12
590817	10629A	MLG	XRM92	Y	2		H67	ENG	N	1/14/2006	3/8/2006	3/18/2006	44964	Y	53	12
590817	10629A	MLG	M3B22	Y	3	Y	H67	BODY	N	1/14/2006	3/8/2006	3/20/2006	999		0	12
590817	10629C	MLG	XSQ39	Y	2		I67	OTHER	N	5/13/2006		5/15/2006	2673		0	12
590817	10629C	MLG	MR265	Y	3	Y	I67	TRAN	N	5/13/2006		5/15/2006	2673		0	12
590817	10629C	MLG	XRM07	N	2		355	OTHER	N	5/23/2006	5/24/2006	5/24/2006	47665	Y	1	12
590817	10629C	MLG	MR328	N	3	Y	355	OTHER	M	5/23/2006	5/24/2006	5/24/2006	47665	Y	0	5
590817	10629C	MLG	XRL80	Y	2		52	OTHER	N	5/31/2006		6/3/2006	4590		0	12
590817	10629C	MLG	XRP66	Y	2		H67	TRAN	N	6/19/2006	6/27/2006	6/29/2006	48107	Y	8	12
590817	10629C	MLG	MR477	N	3	Y	H34	BODY	N	6/20/2006	6/21/2006	6/21/2006	48111	Y	2	12
590817	10629C	MLG	XRL68	N	2		M17	AIR	M	10/16/2006	11/9/2006	11/9/2006	53723	Y	24	2
590817	10629C	MLG	MR509	N	3	Y	H04	BODY	M	11/7/2006	10/16/2006	11/8/2006	53726	Y	0	2
590817	10629C	MLG	XSE29	Y	1		64	AXLE/SUSP	S	1/15/2007		1/24/2007	101		0	12

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APPENDIX C

SAMPLE OF REPAIR PART DATA

ERO	DRIS	DOC #	PART NAME	QTY	PRIORITY	PART $	TOTAL $	NSN	UNIT ISSUE	SUBSYSTEM
IQI51	7002	9420170027365	SEAL,PLAIN	4	5	25.33	101.32	5330015179793	EA	AXLE/SUSP
IQI51	7002	9420170027366	RING,RETAI	4	5	1.77	7.08	5325014792006	EA	AXLE/SUSP
IQI51	7002	9420170027367	O-RING	4	5	0.54	2.16	5331014789898	EA	AXLE/SUSP
IQI52	7002	9420170057102	PLATE,MOUN	1	5	76	76	5340015356438	EA	BODY
IQI52	7002	9420170027370	PLATE,MOUN	1	5	76	76	5340015356445	EA	BODY
IQI52	7002	9420170027369	LOCKING PL	1	12	126.73	126.73	5340015361482	EA	BODY
IQI52	7002	9420170317601	PARTS KIT,	1	12	14.25	14.25	2590013081624	KT	BODY
PSX54	7002	SAL1270487053	FSTOCKFFF	1	2	15003.98	15003.98	5998014455564	EA	TRAN
PSX54	7002	SAL1270457051	FSTOCKFFF	1	2	11479.25	11479.25	1005011918733	EA	TRAN
PSX54	7002	SAL1270027050	FSTOCKFFF	1	2	2255.25	2255.25	2920013786775	EA	TRAN
PSX54	7002	9442070027C09	ANNUNCIATO	1	5	3103.28	3103.28	6350014958700	EA	OTHER
PSX54	7002	9442070027C02	HANDLE,SOC	1	12	35.21	35.21	5120000998544	EA	BODY
PSX54	7002	9442070027C06	WRENCH,BOX	1	12	12.25	12.25	5120013491438	EA	OTHER
PSX54	7002	9442070027C07	WRENCH,BOX	1	12	12.25	12.25	5120013491439	EA	OTHER
PSX54	7002	9442070027C05	SOCKET,SOC	1	12	4.98	4.98	5120001801016	EA	OTHER
PSX54	7002	9442070027C08	WRENCH,BOX	1	12	4.88	4.88	5120010454907	EA	OTHER
PSX54	7002	9442070027C03	SOCKET,SOC	1	12	4.86	4.86	5120013489133	EA	OTHER
PSX54	7002	9442070027C04	SOCKET,SOC	1	12	4.86	4.86	5120013489134	EA	OTHER
PSX54	7002	9442070027C01	GUN,AIR BL	1	12	4.26	4.26	4940003335541	EA	OTHER

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APPENDIX D

ESSENTIAL DATA ELEMENTS

- Armor type: The type of MAS armor kit installed, described as either cab or cab and troop carrier.
- Armoring date: The date that MAS armor is installed.
- Category Code: A code that identifies the type of equipment inducted into maintenance and the criticality of repair.
- Date Received In Shop (DRIS): The date that a vehicle is inducted into maintenance.
- Date LM2: The date that a deadlined vehicle is removed from deadlined status.
- Defect Code: A code used to identify the specific problem with the vehicle inducted for repair.
- Equipment Repair Order (ERO): The document that captures maintenance actions and requirements when a vehicle is inducted into maintenance.
- ERO Cross Reference: The ERO that an active ERO is associated to. Used when a vehicle is evacuated to a higher echelon of maintenance.
- ID Number: The variant or model of the vehicle.
- "M" Days Deadlined: The number of days a vehicle is in deadlined status (Category Code "M").
- Meter: The odometer reading at the time a vehicle is inducted into maintenance.
- National Stock Number (NSN): The stock number used to categorize, identify, requisition, and track system parts.
- Priority: The two digit numeric value that identifies the urgency of need for repair or repair parts.

- Required Delivery Date (RDD): The date that the vehicle manufacturer is required to provide the vehicle to the using unit.
- Scheduled / unscheduled maintenance: The broad type of maintenance a vehicle requires when an ERO is created. Scheduled maintenance is normally for preventive maintenance and planned modifications, while unscheduled maintenance is for corrective maintenance due to system failure.
- Serial number: The vehicle serial number.
- Subsystem: The vehicle subsystem that identifies the location of failure and required maintenance.
- Unit Identification Code (UIC): The five digit code that identifies the unit a vehicle is assigned to.
- Unit: The major Marine Corps operating force unit a vehicle is assigned to.

APPENDIX E

DEFECT CODE INFORMATION AND SAMPLE FREQUENCY

Defect Code	Explanation (1st character)	Explanation (2nd & 3rd characters)	Subsystem	Sched.	Freq.
2	Test Equ./Display Devices		OTHER	N	2
11		Hose, Tubing, Fittings	OTHER	N	1
17		Pumps and Components	OTHER	N	1
22		Steering Components	AXLE/SUSP	N	1
25		Glass Replacement	BODY	N	1
34		Replace	OTHER	N	40
48		Cracked, Broken, Bent	BODY	N	8
52		Annual Preventive Maint.		Y	402
53		Semiannual Preventive Maint.		Y	25
54		Not Applicable	OTHER	N	4
55		Inoperative	OTHER	N	1
56		Minor		N	203
57		Adjust	OTHER	N	7
61		Starter	ELEC	N	2
64		SL-3 Application	BODY	Y	473
66		Fabrication	OTHER	Y	2
67		Modification Application	BODY	Y	75
69		Unknown	OTHER	N	1
113	Ancillary Equipment/Wiring	Injector Systems	FUEL	N	1
234	Test Equ./Display Devices	Replace	OTHER	N	7
254	Test Equ./Display Devices	Not Applicable	OTHER	N	1
255	Test Equ./Display Devices	Inoperative	OTHER	N	1
311	Air Conditioners	Hose, Tubing, Fittings	OTHER	N	2
317	Air Conditioners	Pumps and Components	OTHER	N	7
322	Air Conditioners	Steering Components	AXLE/SUSP	N	1
327	Air Conditioners	Unknown	OTHER	N	8
334	Air Conditioners	Replace	OTHER	N	15
348	Air Conditioners	Cracked, Broken, Bent	OTHER	N	9
350	Air Conditioners	Components Out of Tolerance	OTHER	N	2
354	Air Conditioners	Not Applicable	OTHER	N	2
355	Air Conditioners	Inoperative	OTHER	N	67
356	Air Conditioners	Minor	OTHER	N	3
357	Air Conditioners	Adjust	OTHER	N	3
358	Air Conditioners	Moisture Found	OTHER	N	2
360	Air Conditioners	Safety Deadline	OTHER	N	1
367	Air Conditioners	Modification Application	OTHER	Y	2
371	Air Conditioners	Unknown	OTHER	N	1
402	Component	Brake System	AXLE/SUSP	N	2
425	Component	Glass Replacement	BODY	N	1

Defect Code	Explanation (1st character)	Explanation (2nd & 3rd characters)	Subsystem	Sched.	Freq.
433	Component	High Voltage Wave Ratio	ELEC	N	2
434	Component	Replace	OTHER	N	90
448	Component	Cracked, Broken, Bent	OTHER	N	3
452	Component	Annual Preventive Maint.	OTHER	Y	6
455	Component	Inoperative	OTHER	N	4
456	Component	Minor	OTHER	N	6
457	Component	Adjust	OTHER	N	1
463	Component	Exhaust System	ENG	N	1
464	Component	SL-3 Application	OTHER	Y	4
466	Component	Fabrication	OTHER	Y	3
467	Component	Modification Application	OTHER	Y	6
634	Canvas	Replace	OTHER	N	8
A01	Engine	Alternator, Generator	ELEC	N	2
A07	Engine	Cylinders, Accumulators	ENG	N	2
A11	Engine	Hose, Tubing, Fittings	ENG	N	4
A13	Engine	Injector Systems	FUEL	N	6
A14	Engine	Mechanical Drive Systems	ENG	N	8
A16	Engine	Packing, Seals, Gaskets	ENG	N	10
A17	Engine	Pumps and Components	ENG	N	1
A19	Engine	Regulator Mechanisms	ENG	N	1
A21	Engine	Torque, Sprocket, Drive Mech.	ENG	N	3
A22	Engine	Steering Components	AXLE/SUSP	N	1
A27	Engine	Unknown	ENG	N	7
A31	Engine	Overhaul	ENG	N	1
A34	Engine	Replace	ENG	N	35
A41	Engine	Shorted/Low Resistive Circuitry	ELEC	N	1
A42	Engine	Mechanical/Linkage or Drive	ENG	N	1
A48	Engine	Cracked, Broken, Bent	ENG	N	10
A50	Engine	Components Out of Tolerance	ENG	N	2
A55	Engine	Inoperative	ENG	N	7
A56	Engine	Minor	ENG	N	3
A57	Engine	Adjust	ENG	N	1
A61	Engine	Starter	ELEC	N	6
A63	Engine	Exhaust System	ENG	N	7
A67	Engine	Modification Application	ENG	Y	5
B04	Transmission	Carriage & Mount	TRAN	N	1
B06	Transmission	Control Mechanisms	TRAN	N	3
B11	Transmission	Hose, Tubing, Fittings	TRAN	N	10
B14	Transmission	Mechanical Drive Systems	TRAN	N	3
B16	Transmission	Packing, Seals, Gaskets	TRAN	N	12
B17	Transmission	Pumps and Components	TRAN	N	1
B21	Transmission	Torque, Sprocket, Drive Mech.	TRAN	N	2
B27	Transmission	Unknown	TRAN	N	6
B34	Transmission	Replace	TRAN	N	34
B37	Transmission	Cabling Malfunction	TRAN	N	1

Defect Code	Explanation (1st character)	Explanation (2nd & 3rd characters)	Subsystem	Sched.	Freq.
B48	Transmission	Cracked, Broken, Bent	TRAN	N	10
B50	Transmission	Components Out of Tolerance	TRAN	N	1
B52	Transmission	Annual Preventive Maint.	TRAN	Y	13
B55	Transmission	Inoperative	TRAN	N	25
B56	Transmission	Minor	TRAN	N	9
B57	Transmission	Adjust	TRAN	N	1
B60	Transmission	Safety Deadline	TRAN	N	1
B64	Transmission	SL-3 Application	TRAN	Y	14
B67	Transmission	Modification Application	TRAN	Y	1
C11	Power Pack	Hose, Tubing, Fittings	ENG	N	2
C12	Power Pack	Housing and Castings	ENG	N	2
C16	Power Pack	Packing, Seals, Gaskets	ENG	N	3
C34	Power Pack	Replace	ENG	N	1
C48	Power Pack	Cracked, Broken, Bent	ENG	N	1
D02	Power Train	Brake System	AXLE/SUSP	N	1
D06	Power Train	Control Mechanisms	TRAN	N	1
D11	Power Train	Hose, Tubing, Fittings	TRAN	N	1
D14	Power Train	Mechanical Drive Systems	TRAN	N	7
D16	Power Train	Packing, Seals, Gaskets	TRAN	N	21
D17	Power Train	Pumps and Components	TRAN	N	2
D21	Power Train	Torque, Sprocket, Drive Mech.	TRAN	N	3
D22	Power Train	Steering Components	AXLE/SUSP	N	2
D34	Power Train	Replace	TRAN	N	12
D48	Power Train	Cracked, Broken, Bent	TRAN	N	7
D52	Power Train	Annual Preventive Maint.	TRAN	Y	1
D58	Power Train	Moisture Found	TRAN	N	1
E01	Axle System	Alternator, Generator	AXLE/SUSP	N	1
E02	Axle System	Brake System	AXLE/SUSP	N	44
E06	Axle System	Control Mechanisms	AXLE/SUSP	N	2
E11	Axle System	Hose, Tubing, Fittings	AXLE/SUSP	N	3
E12	Axle System	Housing and Castings	AXLE/SUSP	N	5
E14	Axle System	Mechanical Drive Systems	AXLE/SUSP	N	5
E16	Axle System	Packing, Seals, Gaskets	AXLE/SUSP	N	172
E17	Axle System	Pumps and Components	AXLE/SUSP	N	2
E20	Axle System	Springs, Shocks, Stabilizer	AXLE/SUSP	N	19
E21	Axle System	Torque, Sprocket, Drive Mech.	AXLE/SUSP	N	2
E22	Axle System	Steering Components	AXLE/SUSP	N	32
E23	Axle System	Valves and Valve Components	AXLE/SUSP	N	1
E24	Axle System	Torsion Components	AXLE/SUSP	N	1
E27	Axle System	Unknown	AXLE/SUSP	N	1
E31	Axle System	Overhaul	AXLE/SUSP	N	2
E34	Axle System	Replace	AXLE/SUSP	N	139
E44	Axle System	System Alignment	AXLE/SUSP	N	1
E48	Axle System	Cracked, Broken, Bent	AXLE/SUSP	N	22
E50	Axle System	Components Out of Tolerance	AXLE/SUSP	N	1

Defect Code	Explanation (1st character)	Explanation (2nd & 3rd characters)	Subsystem	Sched.	Freq.
E55	Axle System	Inoperative	AXLE/SUSP	N	1
E56	Axle System	Minor	AXLE/SUSP	N	2
E58	Axle System	Moisture Found	AXLE/SUSP	N	27
E65	Axle System	Sewing Rips/Torn Areas	AXLE/SUSP	N	1
E66	Axle System	Fabrication	AXLE/SUSP	Y	1
E67	Axle System	Modification Application	AXLE/SUSP	Y	15
F02	Suspension System	Brake System	AXLE/SUSP	N	3
F11	Suspension System	Hose, Tubing, Fittings	AXLE/SUSP	N	1
F12	Suspension System	Housing and Castings	AXLE/SUSP	N	2
F16	Suspension System	Packing, Seals, Gaskets	AXLE/SUSP	N	27
F20	Suspension System	Springs, Shocks, Stabilizer	AXLE/SUSP	N	41
F22	Suspension System	Steering Components	AXLE/SUSP	N	21
F24	Suspension System	Torsion Components	AXLE/SUSP	N	1
F34	Suspension System	Replace	AXLE/SUSP	N	28
F48	Suspension System	Cracked, Broken, Bent	AXLE/SUSP	N	19
F67	Suspension System	Modification Application	AXLE/SUSP	Y	1
H01	Body, Frame, Hull	Alternator, Generator	ELEC	N	1
H02	Body, Frame, Hull	Brake System	AXLE/SUSP	N	2
H04	Body, Frame, Hull	Carriage & Mount	BODY	N	29
H10	Body, Frame, Hull	Gun Tube, Breech, Firing Mech.	BODY	N	3
H11	Body, Frame, Hull	Hose, Tubing, Fittings	BODY	N	2
H12	Body, Frame, Hull	Housing and Castings	BODY	N	1
H16	Body, Frame, Hull	Packing, Seals, Gaskets	BODY	N	3
H20	Body, Frame, Hull	Springs, Shocks, Stabilizer	AXLE/SUSP	N	17
H22	Body, Frame, Hull	Steering Components	AXLE/SUSP	N	2
H24	Body, Frame, Hull	Torsion Components	BODY	N	1
H25	Body, Frame, Hull	Glass Replacement	BODY	N	30
H26	Body, Frame, Hull	Painting, Body Work	BODY	N	1
H27	Body, Frame, Hull	Unknown	BODY	N	4
H31	Body, Frame, Hull	Overhaul	BODY	Y	4
H34	Body, Frame, Hull	Replace	BODY	N	243
H36	Body, Frame, Hull	Subassembly Adjustment	BODY	N	2
H42	Body, Frame, Hull	Mechanical/Linkage or Drive	BODY	N	3
H46	Body, Frame, Hull	Low Voltage Power Supply	ELEC	N	1
H48	Body, Frame, Hull	Cracked, Broken, Bent	BODY	N	109
H50	Body, Frame, Hull	Components Out of Tolerance	BODY	N	15
H55	Body, Frame, Hull	Inoperative	BODY	N	8
H56	Body, Frame, Hull	Minor	BODY	N	62
H57	Body, Frame, Hull	Adjust	BODY	N	9
H59	Body, Frame, Hull	Arcing/Burnt Components	BODY	N	4
H60	Body, Frame, Hull	Safety Deadline	BODY	N	2
H61	Body, Frame, Hull	Starter	ELEC	N	1
H63	Body, Frame, Hull	Exhaust System	ENG	N	2
H64	Body, Frame, Hull	SL-3 Application	BODY	Y	1
H65	Body, Frame, Hull	Sewing Rips/Torn Areas	BODY	N	1

Defect Code	Explanation (1st character)	Explanation (2nd & 3rd characters)	Subsystem	Sched.	Freq.
H66	Body, Frame, Hull	Fabrication	BODY	Y	2
H67	Body, Frame, Hull	Modification Application	BODY	Y	675
I16	Armament	Packing, Seals, Gaskets	BODY	N	1
I25	Armament	Glass Replacement	BODY	N	4
I26	Armament	Painting, Body Work	BODY	N	1
I34	Armament	Replace	BODY	N	24
I48	Armament	Cracked, Broken, Bent	BODY	N	4
I55	Armament	Inoperative	BODY	N	2
I57	Armament	Adjust	BODY	N	2
I60	Armament	Safety Deadline	BODY	N	4
I66	Armament	Fabrication	BODY	Y	6
I67	Armament	Modification Application	BODY	Y	181
J04	Cooling System	Carriage & Mount	COOL	N	1
J08	Cooling System	Distribution Systems	COOL	N	1
J11	Cooling System	Hose, Tubing, Fittings	COOL	N	9
J12	Cooling System	Housing and Castings	COOL	N	1
J13	Cooling System	Injector Systems	COOL	N	1
J16	Cooling System	Packing, Seals, Gaskets	COOL	N	6
J17	Cooling System	Pumps and Components	COOL	N	4
J27	Cooling System	Unknown	COOL	N	8
J34	Cooling System	Replace	COOL	N	17
J48	Cooling System	Cracked, Broken, Bent	COOL	N	4
J50	Cooling System	Components Out of Tolerance	COOL	N	2
J55	Cooling System	Inoperative	COOL	N	3
J57	Cooling System	Adjust	COOL	N	2
J58	Cooling System	Moisture Found	COOL	N	1
J67	Cooling System	Modification Application	COOL	Y	3
K01	Electrical System	Alternator, Generator	ELEC	N	19
K02	Electrical System	Brake System	AXLE/SUSP	N	13
K04	Electrical System	Carriage & Mount	ELEC	N	1
K06	Electrical System	Control Mechanisms	ELEC	N	8
K12	Electrical System	Housing and Castings	ELEC	N	1
K14	Electrical System	Mechanical Drive Systems	ELEC	N	1
K16	Electrical System	Packing, Seals, Gaskets	ELEC	N	1
K17	Electrical System	Pumps and Components	ELEC	N	2
K19	Electrical System	Regulator Mechanisms	ELEC	N	5
K22	Electrical System	Steering Components	ELEC	N	1
K27	Electrical System	Unknown	ELEC	N	26
K31	Electrical System	Overhaul	ELEC	N	2
K32	Electrical System	Reflected Power	ELEC	N	1
K34	Electrical System	Replace	ELEC	N	172
K38	Electrical System	Low Power Out	ELEC	N	1
K39	Electrical System	Corroded/Rusted	ELEC	N	1
K40	Electrical System	Open/High Resistive Circuitry	ELEC	N	1
K41	Electrical System	Shorted/Low Resistive Circuitry	ELEC	N	4

Defect Code	Explanation (1st character)	Explanation (2nd & 3rd characters)	Subsystem	Sched.	Freq.
K46	Electrical System	Low Voltage Power Supply	ELEC	N	5
K48	Electrical System	Cracked, Broken, Bent	ELEC	N	7
K54	Electrical System	Not Applicable	ELEC	N	1
K55	Electrical System	Inoperative	ELEC	N	76
K56	Electrical System	Minor	ELEC	N	15
K57	Electrical System	Adjust	ELEC	N	10
K59	Electrical System	Arcing/Burnt Components	ELEC	N	5
K60	Electrical System	Safety Deadline	ELEC	N	5
K61	Electrical System	Starter	ELEC	N	27
K62	Electrical System	Battery	ELEC	N	16
K64	Electrical System	SL-3 Application	ELEC	Y	4
K67	Electrical System	Modification Application	ELEC	Y	31
L05	Fuel System	Clutch, Converter, Couplings	FUEL	N	1
L07	Fuel System	Cylinders, Accumulators	FUEL	N	1
L11	Fuel System	Hose, Tubing, Fittings	FUEL	N	2
L12	Fuel System	Housing and Castings	FUEL	N	1
L13	Fuel System	Injector Systems	FUEL	N	2
L16	Fuel System	Packing, Seals, Gaskets	FUEL	N	8
L17	Fuel System	Pumps and Components	FUEL	N	2
L27	Fuel System	Unknown	FUEL	N	1
L34	Fuel System	Replace	FUEL	N	14
L48	Fuel System	Cracked, Broken, Bent	FUEL	N	6
L55	Fuel System	Inoperative	FUEL	N	2
L56	Fuel System	Minor	FUEL	N	1
L63	Fuel System	Exhaust System	ENG	N	1
M02	Hydraulic System	Brake System	HYDR	N	6
M06	Hydraulic System	Control Mechanisms	HYDR	N	1
M11	Hydraulic System	Hose, Tubing, Fittings	HYDR	N	5
M12	Hydraulic System	Housing and Castings	HYDR	N	1
M16	Hydraulic System	Packing, Seals, Gaskets	HYDR	N	3
M17	Hydraulic System	Pumps and Components	HYDR	N	2
M22	Hydraulic System	Steering Components	HYDR	N	10
M23	Hydraulic System	Valves and Valve Components	HYDR	N	2
M27	Hydraulic System	Unknown	HYDR	N	1
M34	Hydraulic System	Replace	HYDR	N	7
M48	Hydraulic System	Cracked, Broken, Bent	HYDR	N	2
M50	Hydraulic System	Components Out of Tolerance	HYDR	N	1
M55	Hydraulic System	Inoperative	HYDR	N	1
N02	Air System	Brake System	AIR	N	35
N06	Air System	Control Mechanisms	AIR	N	2
N11	Air System	Hose, Tubing, Fittings	AIR	N	41
N12	Air System	Housing and Castings	AIR	N	3
N16	Air System	Packing, Seals, Gaskets	AIR	N	10
N17	Air System	Pumps and Components	AIR	N	2
N19	Air System	Regulator Mechanisms	AIR	N	4

Defect Code	Explanation (1st character)	Explanation (2nd & 3rd characters)	Subsystem	Sched.	Freq.
N23	Air System	Valves and Valve Components	AIR	N	11
N27	Air System	Unknown	AIR	N	12
N29	Air System	Abuse/Unauthorized Maint.	AIR	N	1
N34	Air System	Replace	AIR	N	53
N41	Air System	Shorted/Low Resistive Circuitry	AIR	N	5
N48	Air System	Cracked, Broken, Bent	AIR	N	14
N50	Air System	Components Out of Tolerance	AIR	N	2
N55	Air System	Inoperative	AIR	N	14
N56	Air System	Minor	AIR	N	2
O04	Turret System	Carriage & Mount	BODY	N	1
O16	Turret System	Packing, Seals, Gaskets	BODY	N	1
O31	Turret System	Overhaul	BODY	Y	7
O34	Turret System	Replace	BODY	N	24
O48	Turret System	Cracked, Broken, Bent	BODY	N	1
O55	Turret System	Inoperative	BODY	N	1
O66	Turret System	Fabrication	BODY	Y	8
O67	Turret System	Modification Application	BODY	Y	150
P23	Fire Control System	Valves and Valve Components	OTHER	N	1
Q27	Ignition System	Unknown	ELEC	N	2
Q34	Ignition System	Replace	ELEC	N	3
Q41	Ignition System	Shorted/Low Resistive Circuitry	ELEC	N	1
Q55	Ignition System	Inoperative	ELEC	N	4
Q56	Ignition System	Minor	ELEC	N	1
Q59	Ignition System	Arcing/Burnt Components	ELEC	N	1
Q61	Ignition System	Starter	ELEC	N	2
R11	Boom, Cable, Lift System	Hose, Tubing, Fittings	OTHER	N	1
R23	Boom, Cable, Lift System	Valves and Valve Components	OTHER	N	1
R29	Boom, Cable, Lift System	Abuse/Unauthorized Maint.	OTHER	N	1
R34	Boom, Cable, Lift System	Replace	OTHER	N	5
R37	Boom, Cable, Lift System	Cabling Malfunction	OTHER	N	1
R55	Boom, Cable, Lift System	Inoperative	OTHER	N	1
R56	Boom, Cable, Lift System	Minor	OTHER	N	1
T16	Receiver/Input Circuitry	Packing, Seals, Gaskets	OTHER	N	1
T67	Receiver/Input Circuitry	Modification Application	OTHER	Y	2
U11	Antenna/Transmission Line	Hose, Tubing, Fittings	OTHER	N	1
U34	Antenna/Transmission Line	Replace	OTHER	N	5
U56	Antenna/Transmission Line	Minor	OTHER	N	5
U67	Antenna/Transmission Line	Modification Application	OTHER	Y	8
W50	Data/Digital Systems	Components Out of Tolerance	OTHER	N	1
WIR	WIR	WIR		N	22
X34	Meter	Replace	OTHER	N	2
X55	Meter	Inoperative	OTHER	N	1
X67	Meter	Modification Application	OTHER	Y	1
Y67	Weapons	Modification Application	OTHER	Y	2

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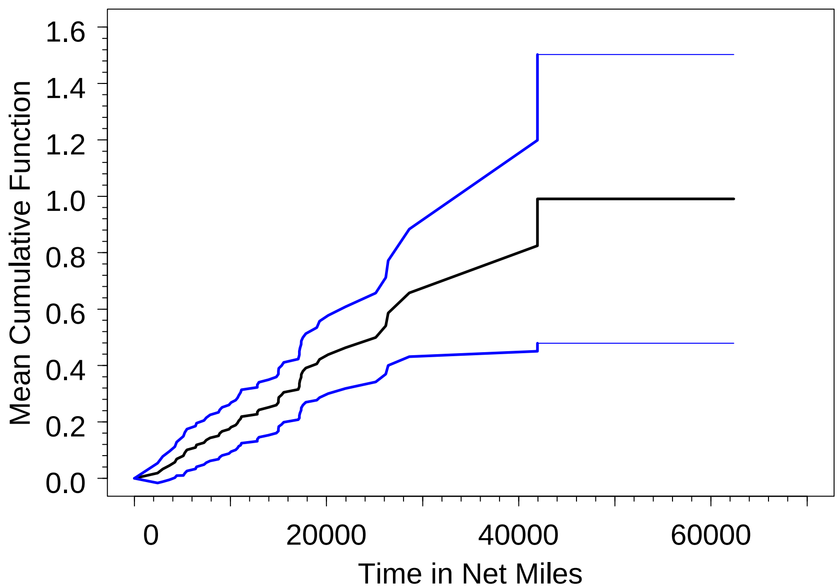
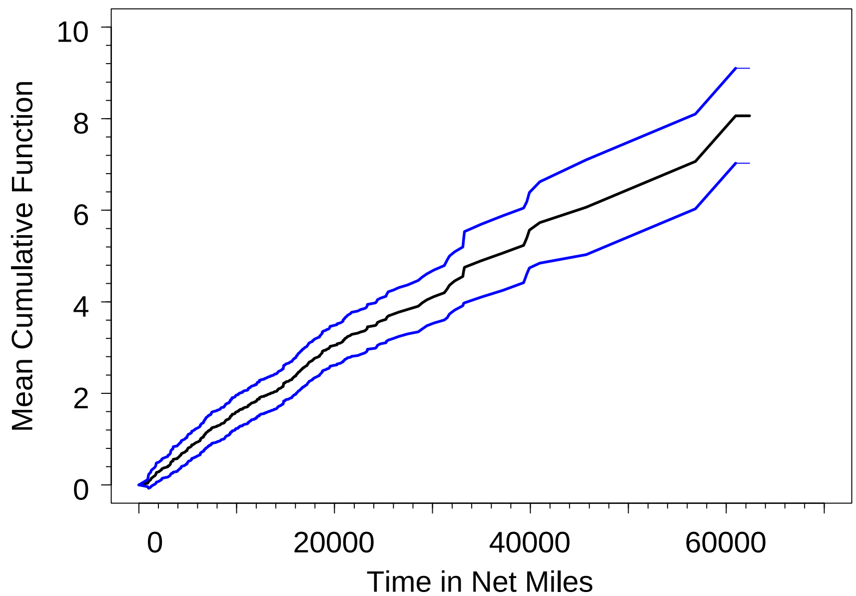
APPENDIX F

ADDITIONAL MEAN CUMULATIVE FUNCTION PLOTS

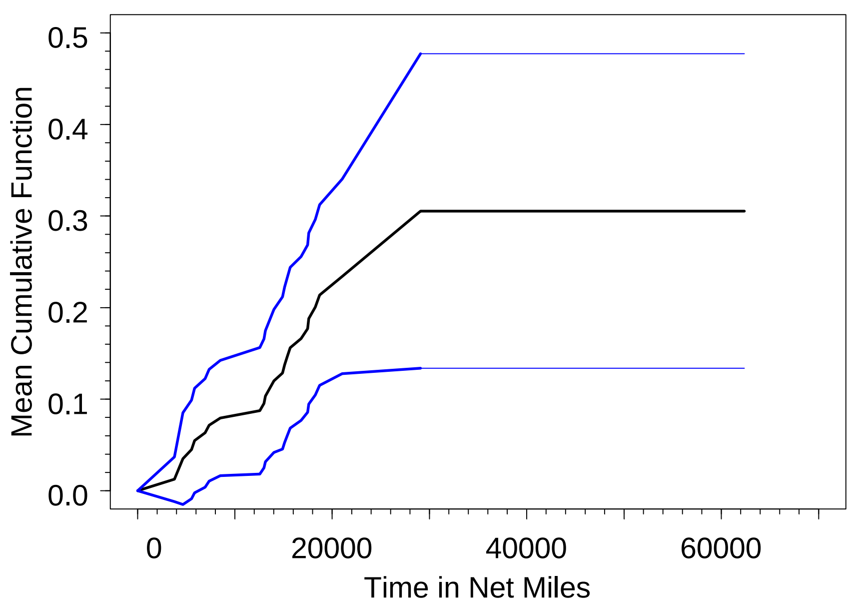
- AIR subsystem failures MCF plot:



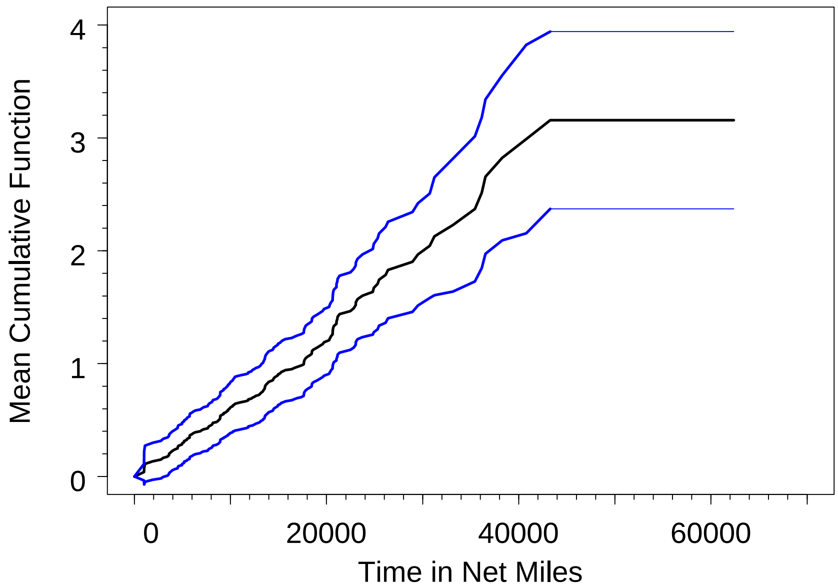
- BODY subsystem failures MCF plot:



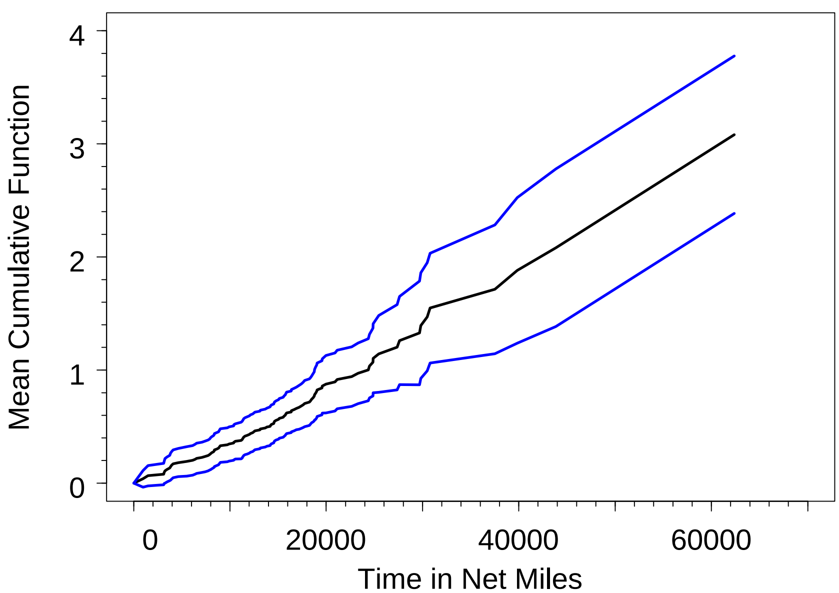
- COOL subsystem failures MCF plot:



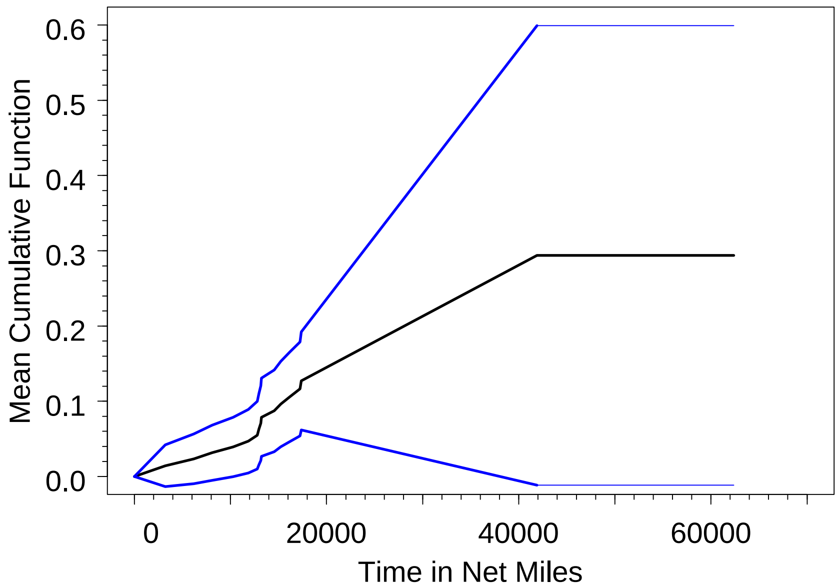
- ELEC subsystem failures MCF plot:



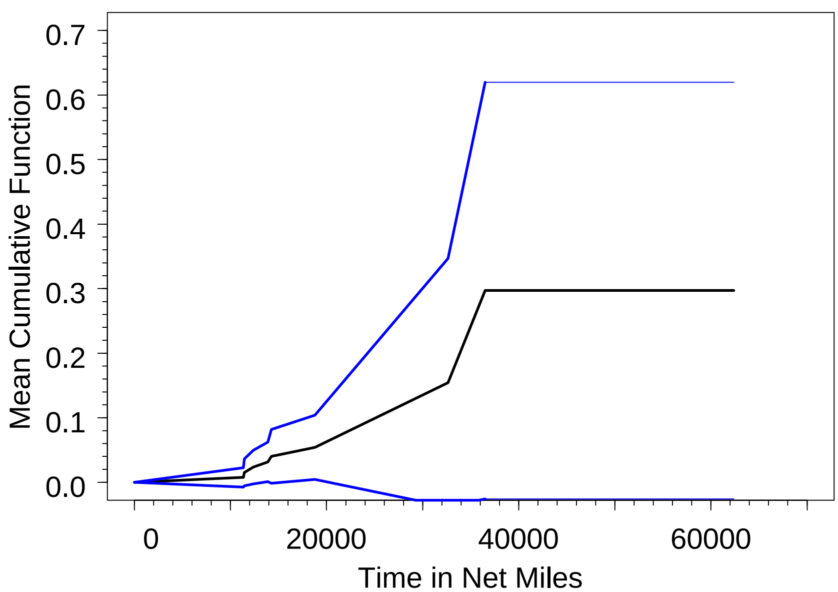
- ENG subsystem failures MCF plot:



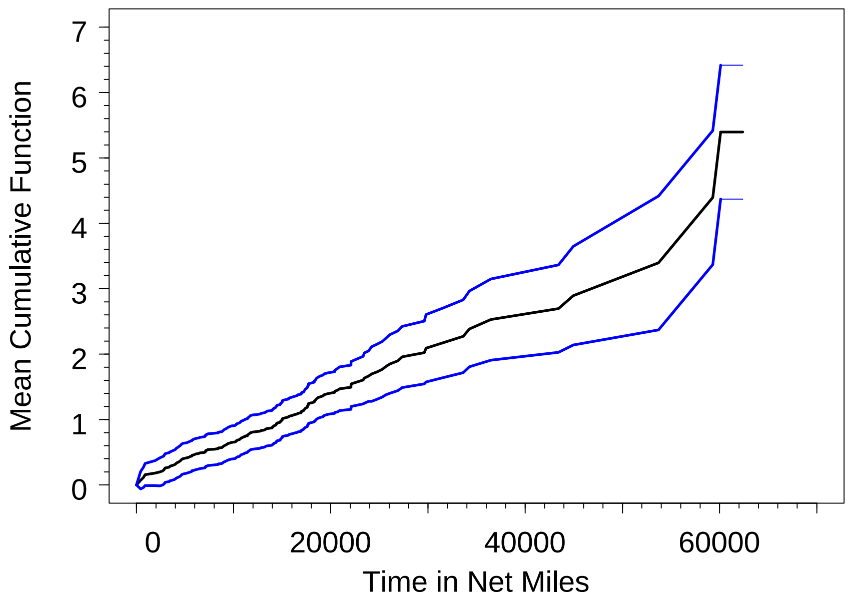
- FUEL subsystem failures MCF plot:



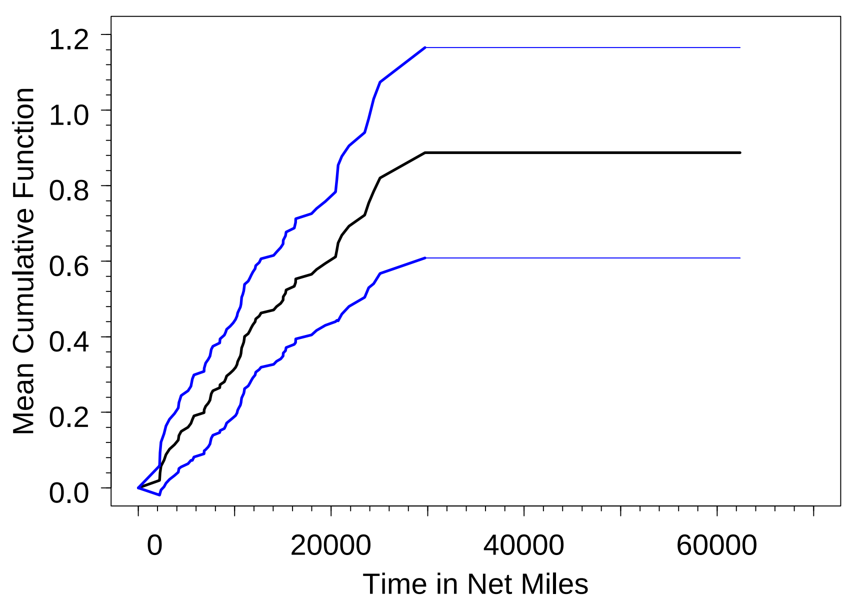
- HYDR subsystem failures MCF plot:



- OTHER subsystem failures MCF plot:



- TRAN subsystem failures MCF plot:



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APPENDIX G

MEAN TIME BETWEEN FAILURE DERIVATION

For a system at time t, the expected time to its next failure is given by

$$\mu(t) = \int_0^\infty R(u,t)\,du\ ,$$

where $R(u,t) = P(X > t + u)$ is the reliability function of the system at time t. The reliability function can be expressed as

$$R(u,t) = \exp\left[-\int_t^{t+u} \upsilon(r,t)\,dr\right],$$

where $\upsilon(r,t)$ is the failure rate. If $\upsilon(r,t)$ is a constant for all values of r and t, failure arrivals follow a homogeneous Poisson process (HPP). Equivalently, the times between failure events follow an exponential distribution. In this case repairs are completely effective in returning the system to "as new" condition. A HPP is the most common example of a renewal process, although not every renewal process is a HPP.

Many repairable systems degrade as they age, so that the arrival rate of failures increases with time. This is often described using a nonhomogeneous Poisson process (NHPP) with an increasing rate of arrivals, such as the following Power Law model:

$$\upsilon(r,t) = \frac{\beta}{\eta}\left(\frac{r}{\eta}\right)^{\beta-1}$$

A Power Law model has an increasing rate of failures if β is greater than one. In this model there is no dependence on t, which suggests that repair returns the system to the condition it was in just before failure occurred.

For a Power Law model the mean time to repair starting at time t is derived as follows:

$$\int_t^{t+u} \upsilon(r,t)dr = \left(\frac{t+u}{\eta}\right)^\beta - \left(\frac{t}{\eta}\right)^\beta$$

$$\mu(t) = \int_0^\infty R(u,t)\,du = \exp\left[\left(\frac{t}{\eta}\right)^\beta\right]\int_0^\infty \exp\left[-\left(\frac{t+u}{\eta}\right)^\beta\right]du$$
$$= \eta\,\Gamma\left(1+\frac{1}{\beta}\right)\exp\left[\left(\frac{t}{\eta}\right)^\beta\right]P\left\{G > \left(\frac{t}{\eta}\right)^\beta\right\}$$

where G is a random variable having a standard gamma distribution with shape parameter $1/\beta$.

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